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AN ANALYTIC MODEL OF COORDINATED EFFORT WITH APPLICATION TO THE PROBLEM OF SURVEILLANCE C^3

by

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October 1978 - May 1979

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A two-level surveillance system is modeled using cybernetic techniques. It is shown that if system entropy is used as a measure of system performance, its steady state average becomes a sensitive discriminate between alternative control modes, such as between central and local control. It also measures the system's sensitivity to variations in sensor resources, their capabilities and the policy by which they are allocated. It is concluded that informationally derived measures of performance, such as entropy, are appropriate for C^3 modeling in many cases and that they can prescribe quantitative tradeoffs in a quite general way.

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Summary

The evaluation of effectiveness of different command control policies for allocating limited resources in hierarchal decision making systems, like the military, requires an analytical model of system behavior. In general, it has been found difficult to describe overall system behavior in mathematical terms. However, in the class of systems which exist primarily to provide information about the military environment, like surveillance systems, some progress has been made which is reported here. In such systems, entropy, i.e., mathematical uncertainty, characterizes the dynamic behavior in a very fundamental way. When the system is in equilibrium, the average entropy measures performance.

In this work, a two level surveillance system is studied. A cybernetic model is developed from which an ergodic Markov process model and the characteristic entropy function are determined. Computer simulation results are presented that show relative performance curves for "central" and "local" control modes. Several levels of sophistication in resource allocation policies are compared for each modality. The effects of communications delays, sensor mobility, and target dynamic behavior are considered. Extensions of the model to more complex surveillance environments is discussed and avenues for further development of the theory are indicated.

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1. Introduction

Analysis of C^3 systems is made difficult by our inability to specify the relationships of communications and control to the macroscopic variables which determine overall system performance. No two problems seem alike, and most analyses are subsystem specific and scenario dependent.

At the root of the difficulties lie two largely unresolved theoretical issues that inhibit the practical application of multi-level systems theory to C^3; 1) analytic models of cooperative/competitive behavior at common command levels and, 2) sufficiently general, yet quantitative, means to characterize the role of information in complex man-machine decision-making systems[1,2] do not exist.

As an example, consider the problem of determining the degree of local antonomy versus centralization of control for decision making in the conduct of military operations. Although an age old military issue, it reappears in popular debate as the technologies of communication, data storage and data manipulation have expanded exponentially during the later half of this century. Even though the general nature of the objectives at various echelons may be similar, they differ in many detailed ways that directly affect their expression in the decisions of the different commanders. Thus, any attempt to quantify system performance, in terms, say of a simple goal-directed behavior model, is extremely difficult. A more sophisticated model is required to measure the relative

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[1] Bandoyopadhyay, R., "Information for Organizational Decision Making - A Literative Review", IEEE Trans. on Sys. Man and Cyb., SMC-7, Jan. 77.

[2] Mahmoud, M.S., "Multi-Level Systems Control and Applications: A Survey", IEEE Trans. on Sys. Man and Cyb., SMC-7, #3, March 77. (p. 125-143)

merits of various control alternatives. Part of the problem in developing such a model is that identical information has different utility for different decision makers. This is the case at the same as well as at different hierarchal levels, and at different times during the evolution of any given systemic process.

It is clear that information, and its quantitative characterization, are essential to the development of a utilitarian theory for C^3. Communications concerns the transmission of information from point a to points b, c, ..., or from person a to persons b, c, ... Control selects an action taken in accordance with a decision or choice, that is based on (or driven by) information. In general, management or command hierachies come only in indirect contact with their physical environment. The commander's image of the environmental situation and his decisions to take specific actions are filtered through intervening levels. So, in fact, informational quantities are the majority, if not the entirety, of the relevant set of system variables in the study of C^3.

In this paper we focus our attention on the second of the problems mentioned earlier, that is, the quantitative characterization of system performance in terms of ordinary measures of information. In order to treat the multi-level class of problems, into which military C^3 surely falls, we shall adopt the coordination concepts of Mesarovic et al.,[3]. A quite general treatment of the laws of information which govern systems has been described recently by Conant[4]. He suggests that "the fact that information theory fits neatly the hierarchal architecture which is so

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[3]Mesarovic, M.D., Macko, D. and Y. Tokahara, "Theory of Hierarchal Multi-Level Systems", New York, 1970, Academic Press.

[4]Conant, R.C., "Laws of Information which Govern System", IEEE Trans. on Sys. Man. and Cyb., Vol. SMC-6, April 1976.

prevalent in systems of many sorts seems very suggestive and indicates that the relation between information and system dynamics is a deep one"[5]. In this paper we shall show that for a dynamic system whose objective is the reduction of uncertainty about the environment, in the face of random behavior by environmental variables, a steady state entropic variable provides a sensitive and quantitative ranking of control policies. Furthermore, we will show that the cybernetic structure, which characterizes behavior at both supremal and infimal levels, may be understood in terms of a very small number of macroscopic, intensive system parameters. Simulation results are presented that support this claim and which strongly suggest the possibility that a more complete analog between cybernetic system dynamics and statistical mechanics and thermodynamics[6] can be developed.

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[5]Ibid., pg 240.

[6]Schnakenberg, J., "Thermodynamic Network Analysis of Biological System", Springer-Verlag, Berlin, 1977.

2. The System

The specific problem investigated in this research concerns allocation of surveillance sensor resources to locate and track objects that are moving in a large area or space, Λ. Each sensor can, at periodic intervals, attempt to detect objects in a much smaller area or subspace, λ, centered about the search coordinates assigned to it for that epoch. A number of such sensor resources are assumed to be available, however, they are not all endowed with the same performance parameters. Each sensor type is characterized by a probability of detection (the probability it will report an object present in its area λ when the object is there) and a probability of false alarm (the probability it will report an object present in its area λ when, in fact, it is somewhere else).

The different types of sensors are assigned to different surveillance subsystem commanders. These subsystems constitute the infimal level of the surveillance system. Each time a subsystem detects an object, its location is reported to a common commander, the overall surveillance commander, "SURVCOM". SURVCOM is the supremal level of a two-level surveillance system. Organizationally, the system is structured as shown in Figure 2.1.

SURVCOM has been tasked to know the location of all the objects in the surveillance space Λ at all times. In practice, however, there are insufficient total sensor assets to accomplish this task perfectly, so SURVCOM must do the best job possible within the constraints imposed upon him by systemic as well as by resource factors. Included in systemic factors are the basic organization structure, the behavior of the infimal level commanders, the mobility of resources and the varying demands that

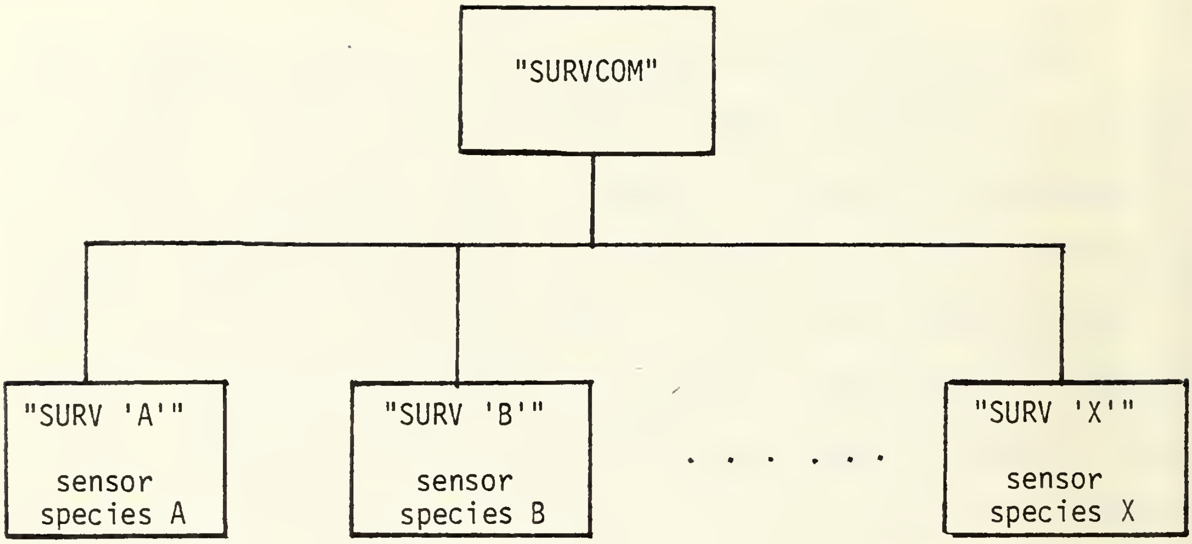

Figure 2.1

Organization Chart of a Hypothetical Surveillance Command

are made upon him by his superiors or customers for the surveillance information. Resource limitations include, in addition to the limited number of sensors, the capacity and time delays of communications with subordinates, time delays subordinates have in communicating with or moving their sensors, and the personnel, processing or data storage limitations that might exist at the various system nodes.

Infimal level commanders have the same overall responsibility as their commander, they must try to keep track of the objects. In addition, they have to follow orders, which he may give them from time-to-time, about where to look or how to deploy their sensors. Besides following orders and trying to keep track of the objects, the infimals may have other local goals or objectives that will enter into the decisions they make. Some of these may be explicitly stated and sanctioned, or originated, by the commander; e.g., to maintain a high morale among the assigned personnel, to conserve limited materials such as fuel or aircraft hours, to maintain a high level of readiness by keeping some fraction of their resources in reserve, etc. Some objectives may be less up front; e.g., establishing an especially high level of efficiency for surveillance vis-a-vis other infimal level commanders in order to enhance personal chances for promotion, maintenance of a high level of informal cooperation with certain other infimal commanders in support of standing personal relationships or former associations, exaggerating the emphasis on training in anticipation of future demands against more elusive objects, etc. The point is, that although each commander adheres to the overall objective of the entire system, i.e., to fulfill its purpose as an organization created to keep track of objects, the variety of the <u>functional</u> goals that exist at the various system nodes will result in a wide range of overall system behaviors and performance efficiencies. Perhaps the only other common goal each commander will have is try to assure that the portion of the system he is responsible for survives, i.e., preserves its fundamental character[7]. It is within this complex individual motivational framework that one must define the role of information, attempt to measure its

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[7]The tendency of systems to "act in such a manner so as to preserve their character" is known as the Principle of LeChatelier. See, e.g., "Living System", James Grier Miller, McGraw-Hill, 1979.

utility and devise a means to differentiate between alternate operational control policies; policies that will involve varying degrees of information transmission and processing.

Two extreme modes of operational control can be envisioned. At one extreme, SURVCOM makes all the decisions about the allocation of all the sensor assets at every time epoch. In this mode, the infimal levels make no operational decisions (they may still be making many administrative decisions that can indirectly effect operational performance), they merely serve as conduits to and from the sensors.

At the other extreme, the local commanders make all operational decisions abouth the deployment of the sensors assigned to their commands; they report to SURVCOM the location of the objects, if and when they detect them. We shall call the first control mode 'central' or 'supremal' control and the second control mode 'local' or 'infimal' control. Obviously, these two modes require radically different communications support systems.

The commander(s) must have an allocation policy for his sensors, regardless of the control mode of the system. The policy, in practice, is the "guidebook" or "rules" a commander uses to make operational decisions about the appropriate action to take for a given (environmental) situation. The policy is constrained by the characteristics of his resources, but, within these constraints, is designed to fulfill his goals. To the extent that constraints and goals can be clearly defined and explicitly described, one may talk about finding "optimum regulation policies". However, in practice, the subjective and variable nature of many of the dimensions of the commander's "goal space" makes the search for an optimum policy somewhat academic. However, a useful approach, and the one followed in this research, is to define a sensitive measure of effectiveness for the commonly held and explicitly stated purpose of the system. With such a measure, one finds the sensitivity of the commonly accepted view of achievement to variations of the constraints, the regulation policy, (and control mode as well) thereby gaining a deeper insight into the true nature of the system behavior.

The constraints placed on commanders of the surveillance system concern, in addition to the number and detection capabilities of their sensor assets, the rapidity with which they can move sensors from place to place in the surveillance space, the communications capacity and communications delays to and from the sensors, and the processing and data handling speed and capacity they can employ to utilize information obtained from prior time epochs to choose the "best" course of action for the next epoch(s). In addition, the prior knowledge (intelligence) commanders have (about the number and dynamic behavior of the objects they are attempting to survey) is important and can be viewed as a constraint.

Constraints permitting, a commander may consider a variety of sensor coverage allocation policies. For example, the commander may just "seed" the space Λ randomly with sensors and wait for the object to come within range, reporting a location as one stumbles unwittingly within coverage of a sensor. Or, once an object is detected, the commanders may try to concentrate sensors into a subspace, Λ_D, in which they are certain the object must be by virtue of their prior knowledge about the objects mobility. Finally, a commander may deploy his sensor resources at any time epoch in such a way as to maximize the probability he will locate as many objects as possible. In order to do this, he uses all the information available to him; that means all he knows about where the objects could conceivably be, (based on the rapidity with which they can maneuver) plus what he has learned from searching various areas in prior epochs in which the objects were not successfully detected. Systemic resources must be, of course, more elaborate to pursue this latter policy than either of the other two.

The three regulation policies and two control modes described above by no means exhaust the possibilities for either. However, they represent some typical C^3 alternatives for which one may desire to measure surveillance system performance. The fact that differing alternatives require different sunk costs and operating costs, that they have differing susceptabilities to counter-measures and deceptions, and that they fulfill, to greater or lesser extent, other more subjective goals of the various decision makers, combine to form a rationale for looking at alternatives in the first place. The purpose of an analysis is only to quantify the sensitivity of the "overall", or "bottom line" measure of system performance to policy and/or constraint/resource changes, and to gain insight into the nature of the system's dynamic behavior and stability.

3. A Cybernetic Model of 'The System'

Nowhere in the preceding description of 'The System' has it been explicitly stated that a model must be specified in order to carry out the analysis. Nevertheless, it must be apparent that we have at least had a 'conceptual model' of a real (either actual or hypothetical) surveillance system in mind. In this section we shall become quite explicit about such a system model. The structure we seek must include all the "relevant" features of the surveillance problem, but at the same time be sufficiently explicit to admit to analysis (in this paper by simulation).

A general form of the cybernetic system model, developed originally by W.R. Ashby[8], forms the basis for the approach followed here. However, important additions have been adopted in order to account for the indirect contact all of the commanders have with their environments.

The Canonical Form

The basic cybernetic model is shown in Figure 3.1. The Environment is sensed; Disturbances are transmitted as inputs to the System. The System transforms the inputs into outputs, the Actions. The nature of the transformation is controlled by the System Regulator, acting in accordance with a regulation policy which has been adopted to achieve the system goals. Prior Knowledge, or Intelligence, is used by the Regulator to assist the formulation of a successful policy. The Actions initiated by the System become Environmental Outcomes. The resultant environmental situation is the source of new Disturbances that stimulate the System, and so on.

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[8] Ashby, W.R., "Introduction to Cybernetics", Wiley, New York, 1956.

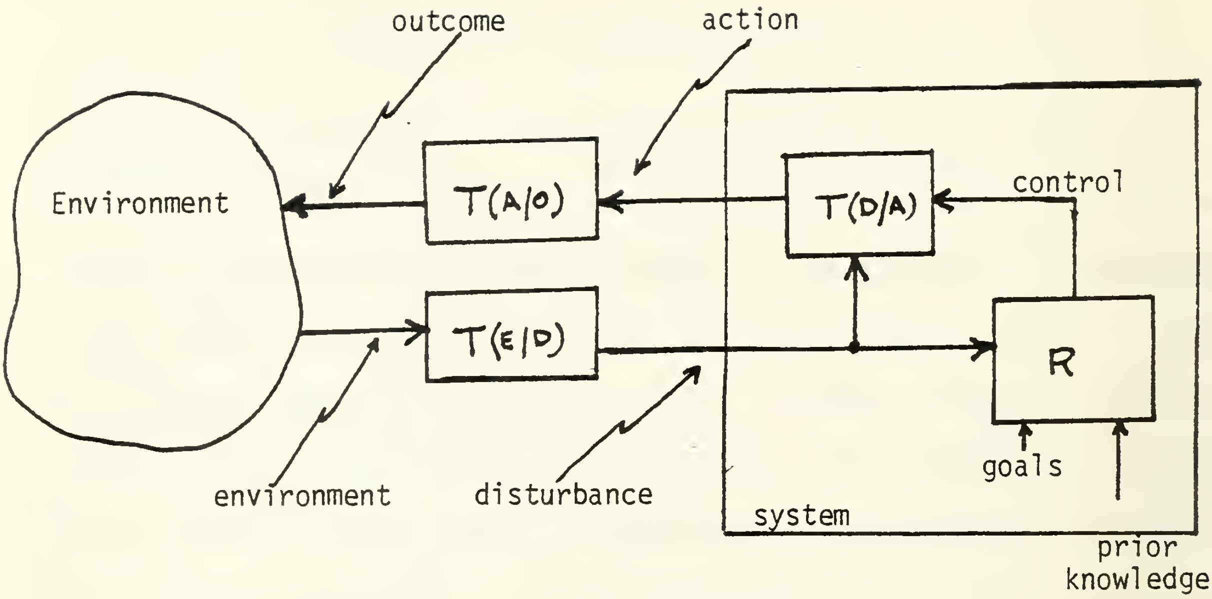

Figure 3.1
The Elementary Cybernetic Model of a System

Consider the application of this structure to the situation encountered by the surveillance commander. Pertinent variables are as follows:

<u>Environmental</u>

. Object location(s)

. Sensor locations

. Natural environmental variables

<u>Disturbances</u>

. Sensor surveillance reports

. Orders from higher level commander

. Intelligence reports (number and type of objects known to be in Λ; semi-static variables)

<u>Actions</u>

. Decisions about new sensor locations

. Reports to higher level commanders

Outcomes

. New sensor locations

. New object locations

Note that each of these variables may be quantified, including, insofar as they relate to the operational problem of tasking the sensors, the orders from and reports to a higher level commander. Also note that each of these variables are microscopic in nature; they describe the "nitty-gritty" behavior of the system as a function of time. If one could observe the actual values of these variables as a function time, the result would be a set of stochastic variables. None of the variables change more frequently than some minimum time interval, t_e. If all the functions are sampled at a rate equal to or less than t_e, the resultant N-dimensional sequence of random numbers can be considered a single realization of an N-dimensional sequence of random variables characterizing the modeled behavior. If one observes sequences that are "typical", regardless of when one looks, the process will be considered to be ergodic, (time and ensemble averages may be exchanged). More importantly, if the process is statistically stationary, so that averages, densities, etc., are independent of time of observation, then the system is in "steady state" or in "equilibrium with its environment".* We shall be interested in determining under what conditions the surveillance system can be considered an ergodic and/or stationary random process.

Transformations

Figure 3.1 models system behavior by assuming that certain of the variables described above are causally related. In the diagram, this is

*The fact that when contrasted with systems in conflict, (such as occur in gaming), information collection and dissemination systems seem to be more readily modeled as systems in equilibrium is of considerable practical importance as one seeks suitable macroscopic measures of performance.

explicitly indicated by boxes labeled, $T(\bar{x}|\bar{y})$, where $\bar{x}$ are the inputs and $\bar{y}$ the outputs of the transformation T.

1. $T(A|O)$: Transformation of Actions to Outcomes

   a) The action of ordering sensor i to search in area λ_j is assumed to produce the Outcome as ordered (i.e., with no error), but with some delay, $\delta_{A|O}$, due to communications delays and/or the time required for the sensor to move from its present to its new location. $\delta_{A|O}$ may not be less than zero, (causality); it may be a known or a random variable.

   b) The action of sending a report of the detected target locations to a higher level commander is modeled in a similar fashion; that is, the Outcome is that the higher level commander receives the report with no errors, but due to communications delays, at some time after the action taken to send it.

2. $T(E|D)$: Transformation of Environmental Situation to System Disturbances

   a) The Environmental situation representing an order from a higher level commander, about how or where to allocate sensor resources, is assumed to be transmitted with no error, but with the possibility of a communications delay, $\delta_{E|O}$.

   b) The Environmental situation represented by the location of an object in the space Λ, and sensors covering the sub-space λ_j results in a disturbance or input to the System in the form of a surveillance report. As with the other transformations, there may be communications delays associated with the preparation and transmission of the reports. But, in this case, it is unreasonable to model the sensor transformations as error free. Sensors are assumed to make errors of two kinds; 1) They may report an object in cell λ_j when it is in cell λ_k, (a flase alarm), or 2) They may fail to report the object in λ_j when it is in λ_j (a false miss).

We shall model the sensors as follows: Let p_j be the probability an object is in cell λ_j. Let η_j be the probability that the sensor j reports an object in cell λ_j. Let $\bar{\mu}$ be the probability that no sensors report the object's location (a miss). The transformation prescribing the combination of the object location and sensor locations that produces the surveillance report can be represented in matrix form as

$$\begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1N} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2N} \\ & & & \\ & & & \\ \alpha_{N1} & \alpha_{N2} & \cdots & \alpha_{NN} \\ \bar{\alpha}_{11} & \bar{\alpha}_{22} & & \bar{\alpha}_{NN} \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ \cdot \\ \cdot \\ \cdot \\ p_N \\ \\ \end{bmatrix} = \begin{bmatrix} \eta_1 \\ \eta_2 \\ \cdot \\ \cdot \\ \cdot \\ \eta_N \\ \bar{N} \end{bmatrix} \qquad (3\text{-}1)$$

In (3-1), the sensors are characterized by their probabilities of detection, α_{jj}, probabilities of miss $\bar{\alpha}_{jj} = 1-\alpha_{jj}$, and probabilities of false alarm, α_{jk} (probability sensor j reports object in λ_j when it is in λ_k). Note that at every epoch, a subset of the α_{jj} must be zero (and $\bar{\alpha}_{jj} = 1$), since there are insufficient sensor assets to cover all N cells of the object space Λ. However, since sensors are moved about and the location probabilities of the target depend on prior events, the sensor transition matrix, $[\alpha]$ and the object location vector $\bar{p}$ are both dynamic, albeit deterministic, entities. $[\alpha]$ and $\bar{p}$ may also depend on natural environmental conditions.

3. $T(D|A)$: Transformation of Disturbances to Actions

If one thinks of the "The System" as a "Black Box", the $T(D|A)$ characterizes the transformation of inputs to outputs, i.e., the transfer function of the system. If the outputs for all the inputs are measured, the resultant transformation would, in the absence of random behavior, completely specify the system if it were an electromechanical or chemical system. However, if one tries to do this in an organizational decision making system, such as the one being studied here, one finds that the same inputs do not always result in the same outputs, and that these deviations are not, at least not all, caused by random behavior. In fact, the system is sentient, it thinks and acts in accordance with the best interest of its own survival and in order to achieve its stated goal. This property, one unique to "Living Systems", is modeled by the Regulator. The Regulator is the thinking (analytical) and decision-making (commanding) element of the system. The Regulator processes the input Disturbances, analyzes the situation, considers constraints and alternatives, (what transformations, i.e., what actions are possible), takes account of the goals, objectives and prior knowledge and decides on a course of action. The decision sets the transformation for the current (and perhaps some future) time epoch(s). The Regulator is the "steersman"* of the system, the controller. Without it one does not have a cybernetic model.

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*Steersman (κυβερνητησ) is the Greek origin of the word Cybernetic.

The model of the regulated transformation is shown in Figure 3.2 with inputs and outputs listed.

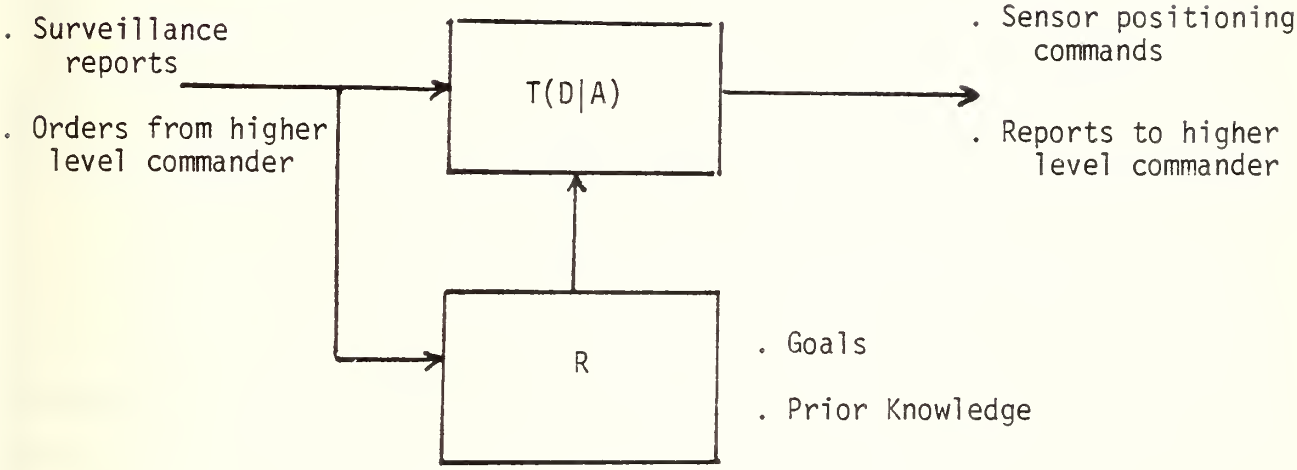

Figure 3.2

Model of "The System"

There may be some time delay, $\delta(D|A)$, involved in the decision making process, as well as in communicating to and from the sensors/environment. This is illustrated in the diagram of Figure 3.3, t_c is the minimum system cycle time.

Regulation Policies and Decision Making

The function of the decision maker in the cybernetic model is to act as the Regulator of the input/output transformation. The regulation policy in given circumstances depends on the commander's assets (or constraints),

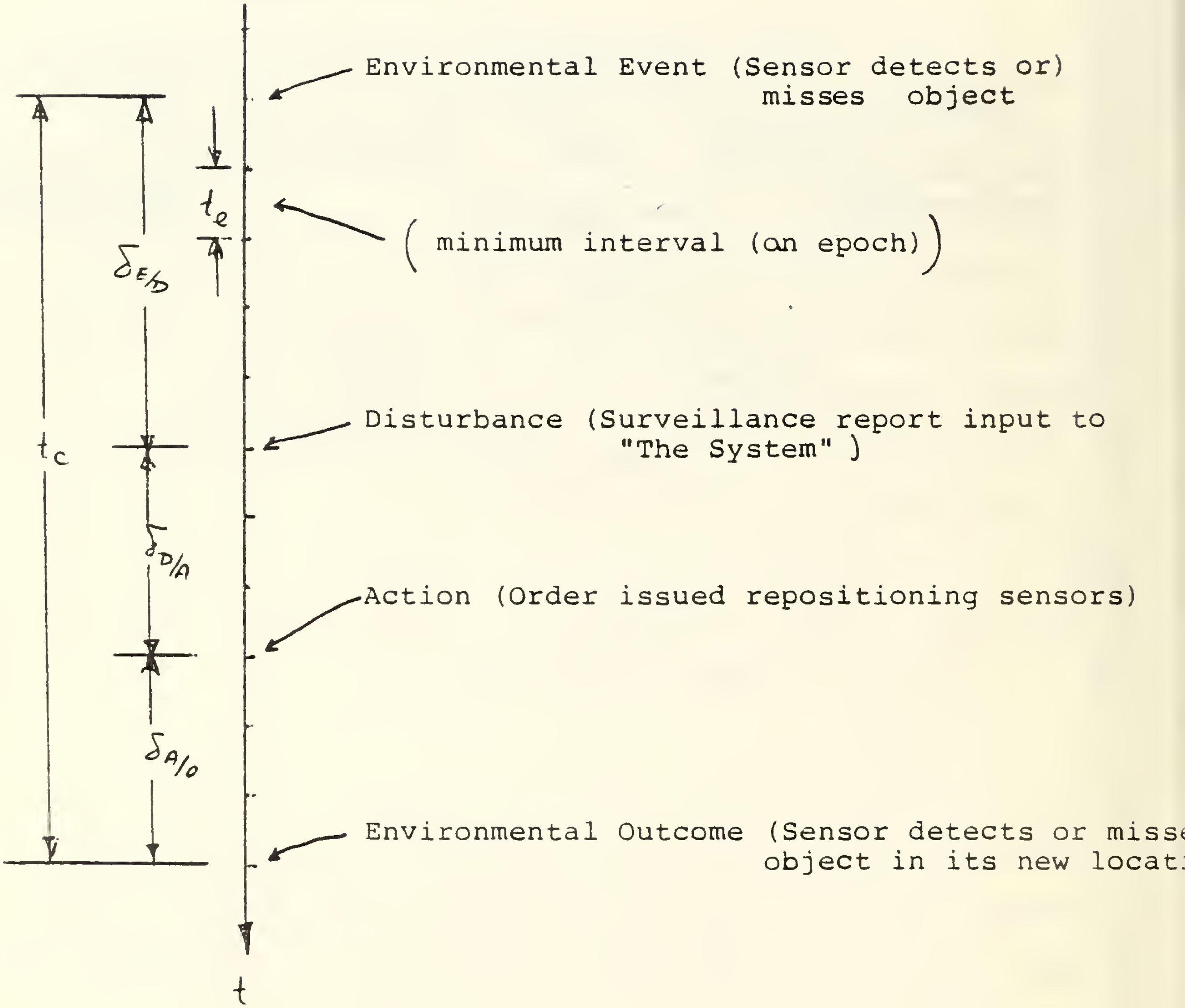

Figure 3.3
Time Line Showing Various
Delays Involved in One Cycle
of Behavior

his goals, and on a number of subjective factors such as personal motivation, etc., as described in Section 2. The subjective aspects are very hard to account for in an overall system analysis. However, much insight is gained by assuming the commander is "goal-directed", i.e., he will act, within his constraints, in such a way as to best, or most nearly, achieve the stated goal of the system; in the present analysis the goal is to keep track of the objects.

The nature of regulation policies is best illustrated by examples:

1. Fixed-Distributed Sensors (FDS)

This is the simplest case, The nature of the sensors is such that they cannot be moved; they are immobile. At the time the sensor system was installed, it was known that the objects movements in the space Λ would be random. Therefore, the sensors were seeded randomly over the space Λ. Since sensors cannot be repositioned, there is no action the commander can take to improve his tracking performance, regardless of the inputs. The System merely serves to pass along the detection reports from the sensors to the higher level commander. Detections occur randomly when the object wanders near a sensor. System performance is solely dependent on the quantity and quality of the sensors.

2. Concentrating Sensors

In this case, the commander is able to move the sensors about, although it may take time.* Once an object is detected, the commander concentrates his sensors in the sub-space dynamically accessible to the object. The commander has prior knowledge about the dynamic behavior,

*Moving sensors about may not only take time, it may consume fuel, reduce readiness, wear out equipment, etc. That is, there may be <u>costs</u> as well as <u>gains</u> associated with this policy.

i.e., the nature and speed of the objects motion, so that he is able to compute the size and location of the object's sub-space at the time his sensors will be on station. Let t_R be the relaxation time for the object.* Then if $t_c > t_R$, the commander cannot react in time to gain any advantage from concentrating his sensors. If $t_c \ll t_R$, one presumes that following a policy of "concentrating sensors" will be superior to the FDS policy. We shall illustrate this advantage in a quantitative and quite general way in the analytical part of this paper.

3. Miss Minimization (Neyman-Pearson Strategy)

If, in any given epoch, all the sensors report "no target", the commander has gained some information about where the object "isn't". One would suppose that this information could be combined, along with the knowledge of target dynamics, to enhance the chance of finding the object on the next epoch. In fact, this is true; this "negative information" can be used as follows:

a. Calculate a revised distribution of target location probabilities, given a miss (Bayes Rule).

$$\hat{P}_i(t_n) = (P_i(t_n) \cdot \bar{\alpha}_{ii})/\bar{\mu}(t_n) \qquad (3\text{-}2)$$

b. Project the new distribution forward to the next search epoch based on knowledge of the object's dynamic behavior.

$$P_i(t_n + \delta_{A/O}) = \sum_j \hat{P}_j(t_n)\, d_{ij}(\delta_{A/O}) \qquad (3\text{-}3)$$

where: $d_{ij}(\delta_{A/O})$ = probability that the object moves from λ_j to λ_i in the time $\delta_{A/O}$.

To make use of this information, the objective must be specified functionally. Suppose the objective is to maximize the probability of

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*This is the elapsed time from a detection until the object can be anywhere in the space Λ, i.e., it's location uncertainty has returned to the maximum.

detecting the object (or equivalently to minimize the probability of missing the object) at the next opportunity. Furthermore, suppose that the false alarm probabilities are independent of the sensors' search area (constant false alarm condition). Then, the probability of a miss is minimized by assigning the sensor with the maximum probability of detection to the most probable cell, the second best sensor to the second most probable cell, and so on in descending order. This is called the miss minimization or Neyman-Pearson policy.

4. Multi-Level System Models

The surveillance system's hierarchal nature merely acknowledges the reality of modern organizational practice in military as well as in civilian institutions. Although the theory of bureaucracy is not at issue in this research, accounting for bureaucratic behavior is.

In the organization of Figure 2.1, two levels are explicitly identified, the supremal level ("SURVCOM") and the infimal level (the Surveillance Sensor "Type Commands"). (There is also a tertiary level, the individual sensor commander, that is implicitly recognized in the indirect coupling that the Sensor "Type Commanders" have with their environments.) There are two views one can adopt in order to describe the two-level, or two-layer, nature of this system. (The terms used are from the canonical cybernetic model shown in Figure 3.1.) The first of these is the "view from the top". It is schematically illustrated in Figure 4.1.

In Figure 4.1 the intermediate level commands appear, as part of the chain of command, to be an integral part of the indirect coupling between the top level commander and the environment he wishes to control. Infimal levels are seen as transformations that compress, filter, and distort information being passed upward, sometimes introducing errors and inevitably introducing delays in the transmission process. Information being passed downward, orders or advisories, is retransmitted to the sensors, and ultimately to the environment, embellished with additional detail and specificity, data elements that are added in the Action-to-Outcome transformation applied to SURVCOM's responses by the intermediate commanders. The downward flow also suffers delays in transmission. In a "smoothly functioning" organization, these delays, will be minimized. An "in-depth-

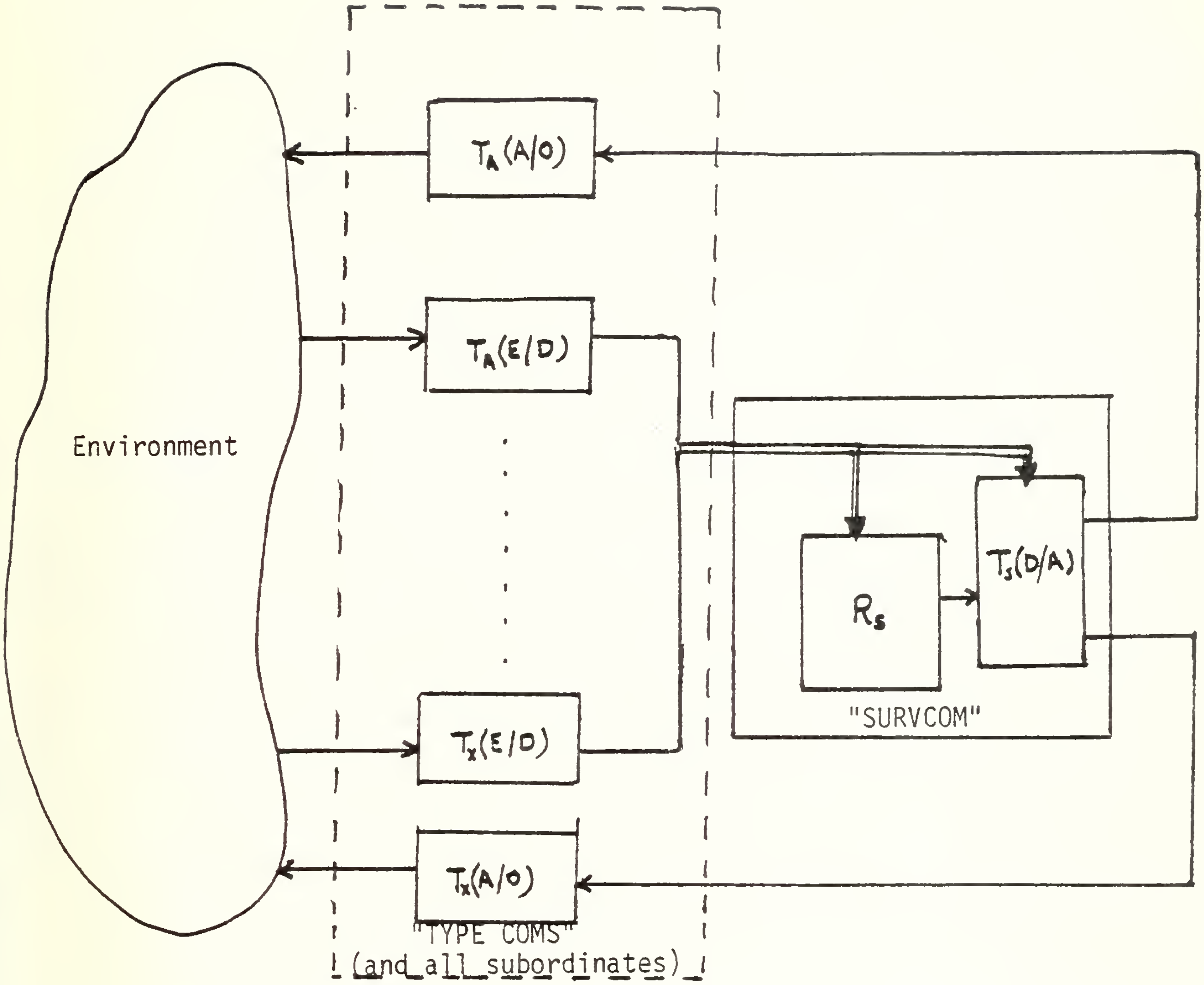

Figure 4.1

The View from the Top

knowledge at the intermediate level of the overall operational flow and of the operator's role in the surveillance process allows him to "anticipate" the actions of his superior and have his resources readied.

The top level commander's success in accomplishing his overall goal, in this case the location of target objects, depends on his ability to indirectly manipulate the sensors and receive their reports. He may, become more successful by understanding and exploiting the bureaucratic response of his overall organization, just as he may excel by exploiting the technical characteristics of his sensor resources. He may in frustration, attempt to change the organization structurally in order to minimize errors and delays. An obvious way to do this is by by-passing, at least for operational matters, the intermediate levels. This choice, remoting and centralizing operation control, ususally requires extra long-haul data communications capacity and larger central staffs and processing facilities. Arguments, pro and con, for centralized vice de-centralized operational control should, at least partially, be based on a rational, quantitative estimate of their relative effects on overall system performance. One object of our research, of which this paper represents a first step, is to provide an analytic methodology to address just such structural realignments of the level of decision-making.

The second view of "The System" is the one maintained by the intermediate level commanders, in this case the Sensor Type Commanders. Their "image" of the organizational process is illustrated in Figure 4.2. The essential difference between the two views is that for the infimal level commanders the supremal level represents but another part of the total environment. As with other environmental elements, his objective becomes

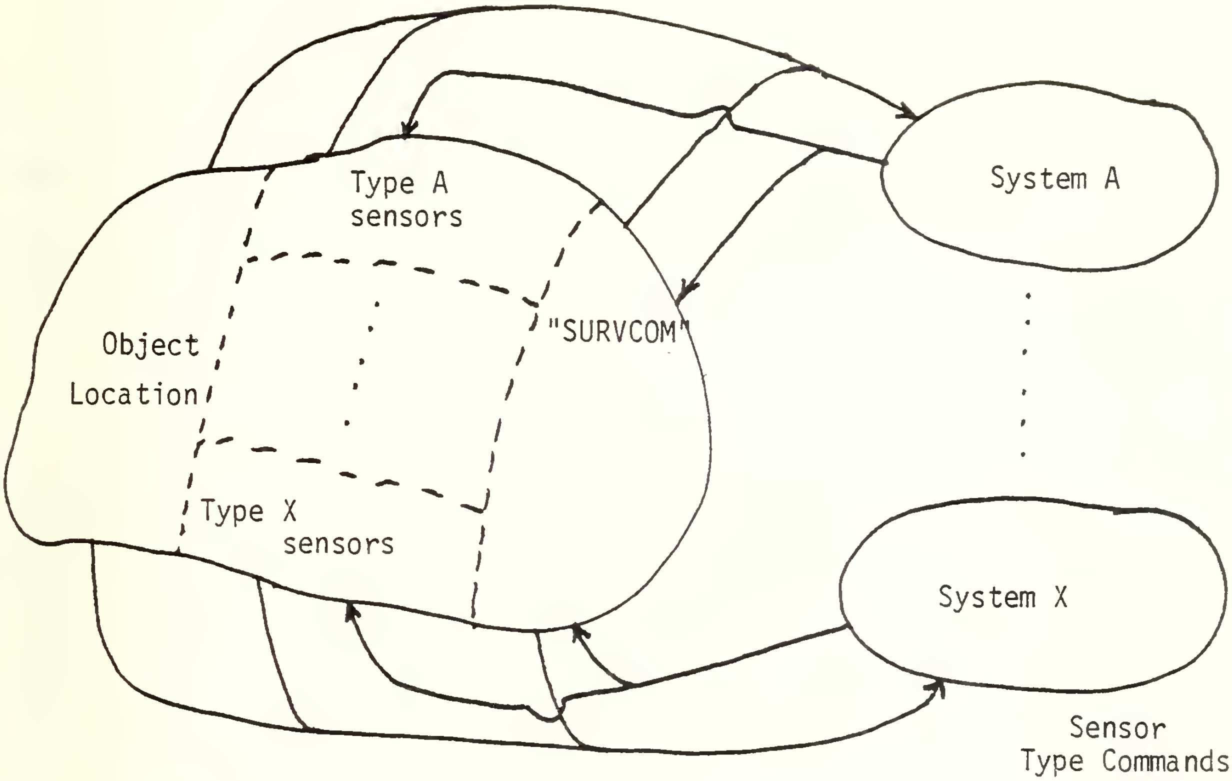

Figure 4.2

The View at Intermediate Level Commands

to respond to environmental stimulli of "SURVCOM" so as to promote his local objectives and goals while maintaining stability (homeostasis).

Another essential feature of this model is that the total environmental situation depends on the Actions of his fellow Type Commanders as well as his own Actions and the behavior of the target objects. It is conceivable that by "cooperative behavior", the infimal commanders may find mutual enhancement of all of their individual goals. That is, the overall system performance, in keeping track of the objects locations can be superior to that obtained by each commander responding solely in order to optimize his own performance. It is also possible for one commander to discover a policy that substantially enhances his own system's performance but that results in drastically inferior performance by his colleagues. This is commonly found in systems that promote "competitive behavior" where the competitors, all theoretically equal, i.e., at common levels of command, are equipped with dissimilar types of resources. If changing the policy of one commander increases his performance, and increases or leaves unchanged the performance of all the other commanders at the same command level, then instituting the policy change is synergistic. If a systematic search is made of all policies for all infimal commanders, adopting a policy if it meets the above criterion and discarding it if it does not, the resulting multi-nodal control policy is called the Pareto optimum policy[9].

In summary, the two views are seen to be quite different. At the supremal level, the infimals are a structually imposed transfer function between the commander and the real environment. Their effects are to be coordinated to achieve the best overall results. Their independence tends to inhibit direct environmental cause and effect behavior. At the infimal level, the supremal commander appears as one more, somewhat unpredictable environmental disturbance to be dealt with, and hopefully controlled by transmitting appropriately designed responses. Other infimal commander's decisions may be affecting the local situation. It may be possible to cooperate with them, necessary to compete with them, or desirable to ignore them. Understanding stability and performance levels of various local control policies, as well as the relative costs of implementation, also motivates the development of an analytical model.

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[9] See e.g., Henderson and Quandt, "Microeconomic Theory", McGraw-Hill, 1958.

5. System Performance

The overall objective of the surveillance system is to determine, at all times, which of N cells, the sub-spaces λ_j of Λ, are occupied by target objects. The cell number, j, is presumed to locate the object to the desired accuracy. The maximum locational uncertainty, that is the maximum entropy, of any one target object is

$$H_{max} = \log_2 N \tag{5-1}$$

If there are M target objects, and they move about independently of one another, the total maximum uncertainty is just MH_{max}. In order to simplify the discussion, we consider one target object in this analysis. Generalizations to objects whose movements are not completely independent and whose uncertain whereabouts is of unequal utility is left for a future development.

Let D be the number of cells which could possibly contain the target object after one time epoch. Then the minimum uncertainty is taken as

$$H_{min} = \log_2 D \ . \tag{5-2}$$

The objective of the surveillance system is to maintain the actual system entropy

$$H = \sum_{i=1}^{N} P_i \log_2 (1/P_i) \tag{5-3}$$

as close to H_{min} as possible. If one observes the behavior of H over a long period of time, as seen by "SURVCOM", it might appear as shown in Figure 5.1.

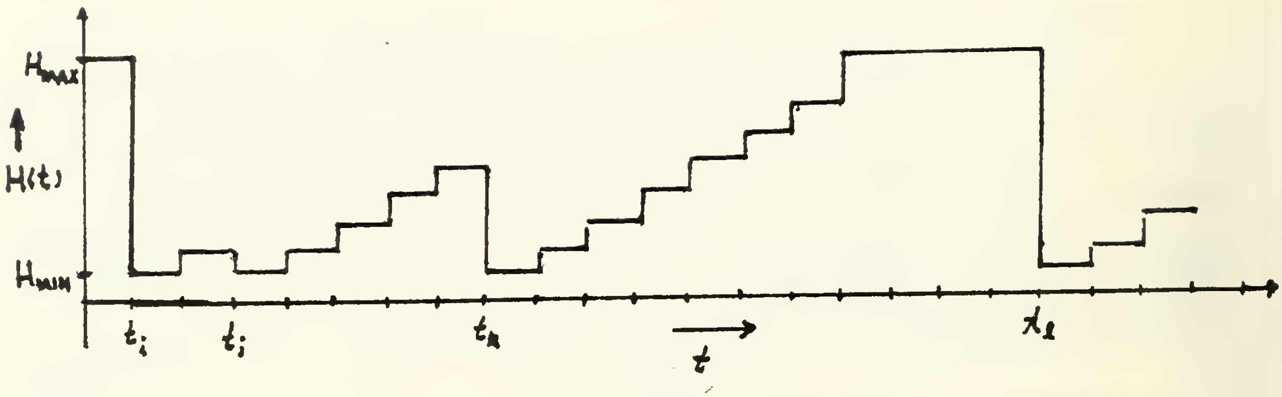

Figure 5.1

A "Typical" Behavior Pattern of System Entropy

When the object is completely lost, H is at H_{max}. Immediately after a detection by a sensor, it falls to H_{min}. If it is re-detected in the next time interval, it stays at H_{min}. If not, H grows; the amount it grows depends on D as well as the search policy. The correct distribution of probabilities to use in Eq. (5-3) is given, at each time tick, by Eq. (3-3). At any time, the object may or may not be re-detected. If it is, H falls to H_{min}, if not, the area of uncertainty grows.

Eq. (5-2) gives the minimum uncertainty because it has been postulated already that no Action can occur in a time less than one epoch. Thus, by the time a commander can make any use of his newly acquired knowledge that the target is located in cell λ_j, the target may already have moved to one of D-1 adjacent cells, or have stayed in the cell in which it has just been found. In terms of our previous mathematical notation,

$$D = \text{Number of non-zero } \{d_{ij}\}, \ \nu \ i\varepsilon N, \tag{5-4}$$

assuming that the number of cells to which it may move is independent of its location.* Clearly, D is a measure of the target's <u>dynamic</u> behavior. (For example, it is proportional to the square of the maximum velocity of a randomly manuevering target object.)

Although H(t) is clearly a random process, the character of its behavior is strongly influenced by the capabilities and the quantity of surveillance sensors, by the dynamics of the object and by the size of the space. Presumably it also depends on the organization of the system and resource allocation policy. A useful theory must distinguish, as sensitively as possible, between control policy alternatives. It must also indicate, in a quantitative way, the costs/benefits associated with perturbations of systemic constraints/resources.

Using our present microscopic model as a guide, it is possible to define several important, intensive macroscopic system variables that grossly determine the operating regimes: "Search", "Surveillance" and "Tracking". These are as follows:

a. $N = \Lambda/\lambda$: Size of the Object Space (Number of cells)

b. D (Eq. (5-4)): Dynamics of the Object

c. $S = \sum_{i=1}^{N} \alpha_{ii}$: Sensor Coverage+

It is extremely useful to consider the operating point of a particular

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*An assumption we maintain in part by having the spatial index set closed, i.e., $\lambda_{N+j} = \lambda_j$.

+Recall that α_{ii} is the probability of detection in cell i. Although this varies from epoch to epoch, the sum is constant, providing sensors are allocated unambiguously. Although some policies may permit overlap, we retain the unambiguous definition of S as our measure of system potential.

system to be established by its location in the space defined by a specific detection coefficient, $\gamma_d = S/N$, and a specific holding coefficient, $\gamma_h = S/D$. This space is illustrated in Figure 5.2.

First note the area is bi-sected by the line D = N. The operating point lies in the Regions B&C of the diagram, $D \geqq N$, if either the target dynamic, or the minimum time epoch (sensor re-visit time), or both, are so large that the target location can always expand to fill the entire space by the time the sensors look for it again. This is the pure "Search" condition. Knowledge of the target's prior location is of no value.* ($H_{max} = H_{min}$). Performance is largely set by γ_d. For $\gamma_d > 1$, Region C enough surveillance coverage has been provided to more than cover every possible target cell at every look. If $\gamma_d < 1$, Region B, detection and false alarms events are determined by the ordinary means of detection theory.

When D < N, knowledge of the object's prior location is, in general, of use in deciding where to look next. In this operating regime Regions A, D & E, a commander can concentrate his resources (assuming they are sufficiently mobile) in the restricted area that the target can occupy to improve his chances of re-detection. If his surveillance coverage substantially exceeds the target maneuverability, $\gamma_h >> 1$, he can, in principle maintain track of the target once it has been detected. Thus, in the region $\gamma_h > 1$, Region D & E, the system can only be in one of two possible states; "Search" or "track".

The triangular region defined by $\gamma_h < 1$, $\gamma_s < 1$ and $\gamma_h > \gamma_s$ (i.e., D < N), is the "Surveillance" operating regime (Region A). Here, there are sufficient surveillance sensor resources to cover the entire space Λ,

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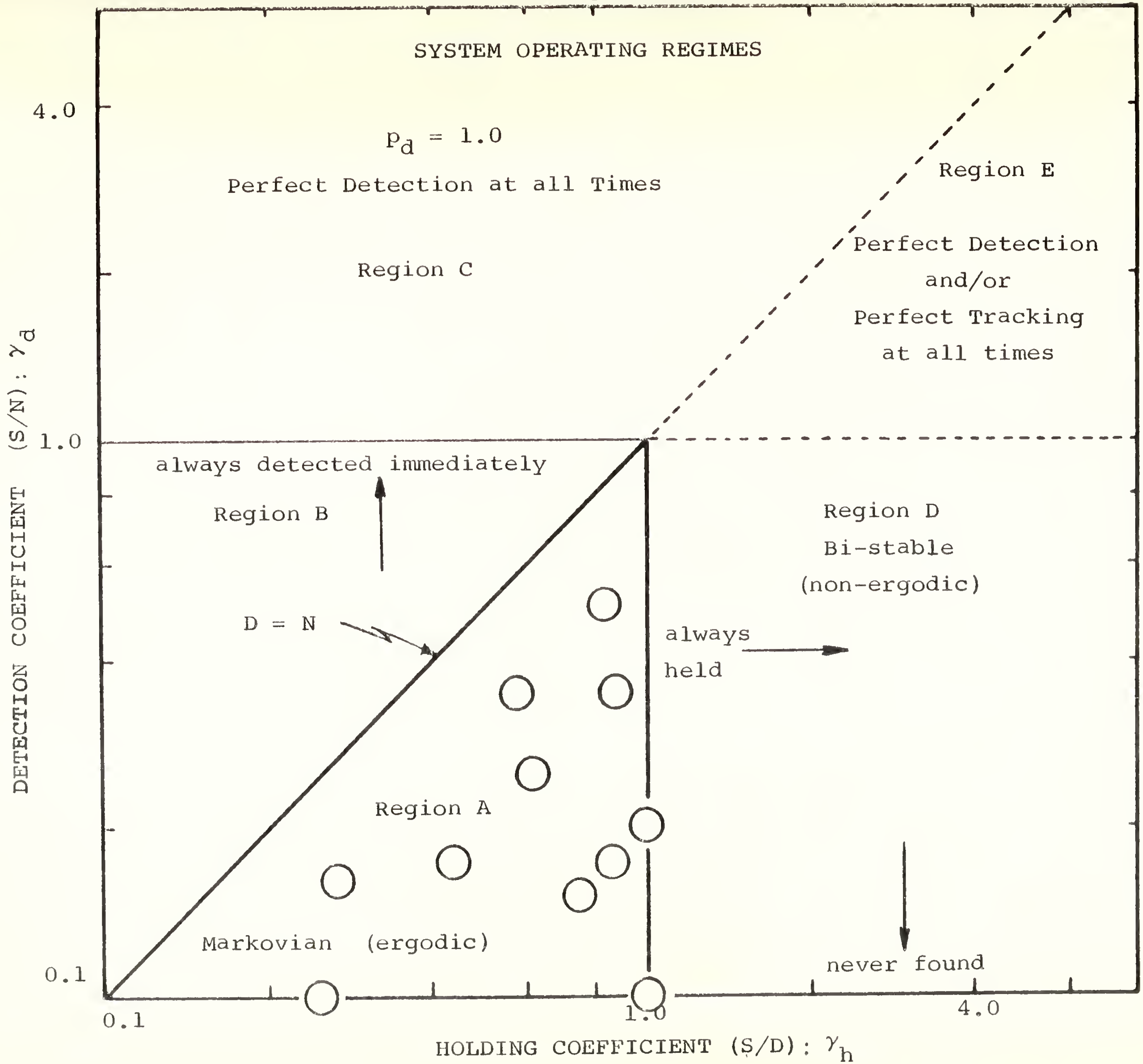
*It is of no value to the surveillance process per se. It may be of value to some other system, a weapon system for example, but only if the receipients response time is less than t_e.

Figure 5.2


SYSTEM OPERATING REGIMES
$P_d = 1.0$
Perfect Detection at all Times
Region C
Region E
Perfect Detection
and/or
Perfect Tracking
at all times
always detected immediately
Region B
D = N
Region D
Bi-stable
(non-ergodic)
always
held
Region A
Markovian (ergodic)
never found
4.0
1.0
0.1
0.1
1.0
4.0
DETECTION COEFFICIENT (S/N) : γ_d
HOLDING COEFFICIENT (S/D) : γ_h

or even the sub-space Λ_D. But $\Lambda_D < \Lambda$ (target partially located) suggests that through proper manipulation of the resources, the times between re-detections may be kept small and the average system uncertainty can be kept close to H_{min}. If the resources are poorly controlled, times between detections may be long and the average uncertainty may be much closer to H_{max}.

It is in the "Surveillance" operating regime that we wish to establish the role of information to determine, in a quantitative way, the cost of communications delays and to distinguish relative value of alternative control policies and between alternative modes of control.

In the Surveillance operating regime, the behavior of the system can be modeled as a simple first-order Markov process. We make the following state identifications:

S_0 : System in search. Object completely lost.

S_1 : Object just detected.

S_2 : Object detected on previous epoch. First re-detection attempt unsuccessful.

S_3 : Object detected two epochs ago. First and second re-detection attempts unsuccessful.

S_{M-1} : Object detected approximately M epochs ago. Subsequent re-detection attempts unsuccessful. If next re-detection fails as well, object will be completely lost again, i.e., system returns to state S_0.

Each of these states is accompanied by a characteristic entropy that depends, primarily, on the target manueverability. However, the probabilities of transitioning to the next state, or back to S_1, depends strongly on the system resources, S, and the way they are managed. State transitions are illustrated schematically in Figure 5.3.

If the probabilities of the system being in each of the M states at step n of the Markov process is given by the vector $\bar{\rho}(n)$, then, q steps later

$$\bar{\rho}(n + q) = [P]^q \bar{\rho}(n)$$

where the state transition matrix [P] is, from Figure 5.3,

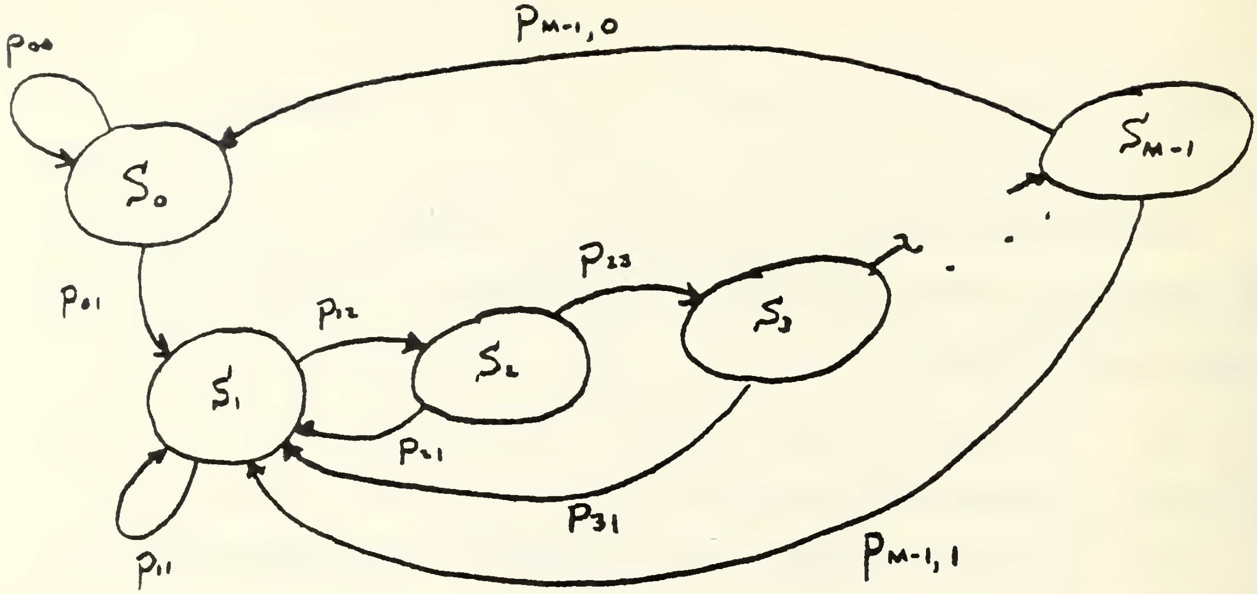


Figure 5.3
First Order Markov Chain Model
of the Surveillance Process

$$[P] = \begin{bmatrix} P_{11} & P_{21} & P_{31} & \cdots & P_{M-1,1} & P_{01} \\ P_{12} & 0 & 0 & \cdots & & 0 \\ 0 & P_{23} & 0 & \cdots & & 0 \\ \vdots & & & & & \\ 0 & 0 & & \cdots & P_{M-1,0} & P_{00} \end{bmatrix} \qquad (5\text{-}6)$$

An important feature of this model is the on-going, more or less "steady-state", type of behavior that the system exhibits. This is only true in the "Surveillance" regime. Note that as long as none of the transition probabilities of Figure 5.3 are identically zero, the system has no final or terminal states. That is, over time, it will cycle around and continually reach every state. On the average, it will be in each state an amount of time determined by the stationary state probabilities, $\bar{\rho}_s$. These can be determined from the state transition matrix, Eq. (5-6) alone.*

Since each state has a characteristic uncertainty, the average uncertanity of the system is given by

$$E[H] = \bar{H}^t \cdot \bar{\rho}_s \qquad (5\text{-}7)$$

where $\bar{H}$ is the characteristic entropy vector associated with system states. On the average, the surveillance system is supplying

$$I = H_{max} - E(H) \text{ bits,} \qquad (5\text{-}8)$$

of information about the location of the object. A dimensionalless, but informationally based measure of system effectiveness is given by computing the fraction of the maximum available information that, on the average the system produces. Thus,

$$\tilde{I} = I/(H_{max} - H_{min}) \qquad (5\text{-}9)$$

measures system performance in a very fundamental way. We shall use $\tilde{I}$ as the measure to distinguish between control modes, to rank regulation policies and to investigate sensitivity to such things as communications delays, the quality and quantity of system assets (sensors) and their mobility.

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*There are a variety of ways to compute $\bar{\rho}_s$ from [P]. A rather simple numerical method is to raise [P] to successively higher powers until the columns are all identical. Every column is then equivalent to $\bar{\rho}_s$.

6. The Computer Model

The cybernetic model has been applied to a simple computer model of the search process. This model consists of a single target free to move in a space of numbered cells. Two searchers investigate the cells with limited sensor resources according to specified rules. The searchers make use of the information obtained in unsuccessful searches to attempt to improve their performance in the next timestep. Because the model is very simple, state entropies and transition probabilities between states can be determined from the repeated trials.

The model can be initialized in either of two ways:

1. with the target lost; the model then gives the entropy of the final or 'lost' state. This is called the <u>search</u> mode.
2. with the target detected; at the previous timestep the searchers then attempt to 'hold' the evading target and the model gives transition probabilities between intermediate states and the entropies associated with those states. This is called the <u>surveillance</u> mode.

Each information handling policy must be run in both modes to obtain the data required to complete the model. The search mode will not be mentioned further in this report, except to indicate how the computations are performed.

The user controls the model by specifying the number of cells in the space, N, and the ability of the target to evade the searcher. This ability is determined by the <u>dodge</u> variable, D. This variable is closely related to the <u>dynamic</u> variable of the theory. The variable D is best introduced by an example: suppose that D = 3, then if the target is located in cell k at timestep n, it may be in cell k-1, k or k+1 at timestep n+1. A value of D = 5 would make cells k-2, k-1, k, k+1, and k+2 accessible.

When D is 'small' the searchers have no difficulty holding the target, while a 'large' D means that the target almost always escapes. Here 'small' and 'large' must be determined in terms of the other variables of the model.

The searchers are labeled A and B. The capability of each searcher is determined by two parameters: the number of cells which it can search in each timestep, L_A and L_B, and the probability of detection for each searcher, α_A and α_B. This is the probability of detection, given that the searcher examines the cell occupied by the target. The capability of a searcher is the product of number of cells it can investigate times the probability of detection in each cell. Thus $L_A * \alpha_A$ measures the capability of searcher A. Interesting cases occur when $D > L_A * \alpha_A + L_B * \alpha_B$, ($\gamma_d < 1$), otherwise, the target never manages to evade successfully. In most of the cases examined values of $\alpha_A = 0.5$ and $\alpha_B = 1.0$ have been used to provide contrast between perfect and imperfect capability.

Because α_A and α_B have effectively been fixed in all of the cases discussed here, a case is determined by the four numbers, N, D, L_A, and L_B. False alarm probabilities have been set to zero.

The computer model goes through three phases during each timestep. Each phase denotes a change in value of the location probability vector $\bar{p}$. At the beginning of each timestep, the searchers are about to commence their search on the basis of the location probabilities available to them. Assume that the target is not detected. Then after the search each searcher has more information about the target's location because, presumably, it has learned from the failure of the search. The entropy of the system is decreased in this phase, but the searchers are unable to act until the next timestep. Before then, the target manuevers, which means that the location probabilities change the entropy increases, and the searchers must consider a larger search region when they re-allocate their sensors.

To understand this process in greater detail, consider the following example: The stated conditions of the model are (10, 5, 2, 2). This means that the space contains 10 cells, the dodge variable, D = 5; because $L_A = 2$, searcher A can examine two cells, as can searcher B because $L_B = 2$. Suppose that the target was detected in the previous timestep in cell 6. At the beginning of this timestep the location probability vector is:

cell #	0	1	2	3	4	5	6	7	8	9
$\bar{p}$:	{0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.0}

Now suppose that searcher A examines cells 4 and 5 while searcher B examines cells 6 and 7. No detection is made. As a result of the search we can be sure that the target was not in either cell 6 or cell 7 because $\alpha_B = 1.0$, but some probability remains that it is in either cell 3 or cell 4 because $\alpha_A = 0.5$. In these cells the location probability has been reduced by a factor of $\bar{\alpha}_A = 1.0 - \alpha_A = 0.5$ so that the <u>unnormalized</u> location probabilities are:

cell #	0	1	2	3	4	5	6	7	8	9
$\bar{p}$:	{0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.2	0.0}

and the <u>normalized</u> location probabilities for phase II are (see Eq. 3-2):

$\bar{p}$:	{0.0	0.0	0.0	0.0	.25	.25	0.0	0.0	0.5	0.0}

The location probabilities for phase III are calculated by redistributioning the probability from each cell over the cells accessible from it if the target were to be evading from that location. Thus the 0.25 probability of cell 4 is equally distributed over cells 2 through 6, the 0.25 from cell 5 over cells 3 through 7, and the 0.5 from cell 8 over cells 6 through 0 (because the universe closes on itself). At the end of this timestep the location probability vector has become (see Eq. 3-3),

cell #	0	1	2	3	4	5	6	7	8	9
$\bar{p}$:	{0.1	0.0	.05	0.1	0.1	0.1	0.2	.15	0.1	0.1}

This vector becomes the basis of the search decisions for the next timestep and the process is continued.

Note that it is physically impossible for the target to be in cell 1. It is somewhat surprising that cells 6 and 7 are the best place to look because they were examined unseccessfully last timestep, but they have high probability values because there are a number of ways that they could be occupied.

In this example the information picture has been constructed as it might be seen by a commander who was coordinating the search efforts of A and B. A similar picture can be constructed from the data available to A, or to B, but it will be different, and search decisions based on the three pictures will not coincide.

It is important to realize that the final location probability picture at phase III depends upon the search strategy used in the timestep. For example, suppose that the cells searched by A and B are interchanged in the example developed above. Now searcher B examines cells 4 and 5 while searcher A examines cells 6 and 7. If a detection is not made, the unnormalized location probabilities are:

cell #	0	1	2	3	4	5	6	7	8	9
$\bar{p}$:	{0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.0}

and the phase III picture becomes:

cell #	0	1	2	3	4	5	6	7	8	9
$\bar{p}$:	0.1	0.0	0.0	0.0	.05	0.1	0.2	0.2	0.2	.15

which is quite different from the earlier result. In particular, there are now three cells where the location probability is zero, where formerly there was only one. The difference occurs because the evasion process is more effective from the final picture of the first example (after search) than it is from the second.

Obviously even such a relatively simple example can lead to a number of final pictures which are subtly different. While the detailed information contained in the location probability picture is required for tactical planning, the excess detail tends to obscure differences and make comparison between pictures more difficult.

A basic tool in the cybernetic approach is the assignment of <u>entropy</u> at the end of each timestep. The entropy,

$$H = \sum_{i=1}^{N} p_i \log_2 (1.0/p_i); \quad p_i \neq 0 , \tag{6-1}$$

at the beginning of the timestep was 2.322 and at the end 3.084. When the search strategy was revised, the final entropy became 2.684.

It is apparent that the final entropy from the second strategy is significantly smaller than from the first. The lower value reflects the fact that with strategy 2 the target is contained within seven cells, while with the first nine were accessible. Without commenting upon the ability of the strategies to detect the target in this timestep, it is clear that the second leaves the searchers with a smaller region to search in the next timestep when they fail in this one. Thus it is a better <u>tracking</u> or <u>containment</u> strategy, and this characteristic has been faithfully reproduced by the reduction of entropy.

Seven control mode/regulation policy combinations have been examined in the computer model. They are listed in Table I.

TABLE I. Control Mode/Regulation Policy Combinations Tested

I. Local Control

A. Search of the cells which have the highest probability of containing the target on the basis of the information available to the individual searcher.

B. Each searcher searches randomly over the entire target space.

II. Central Control

A. The top level commander directs the most capable searcher to the highest probability cells and the other searcher to the next highest probability cells on the basis of the composite picture which he has generated from their previous reports.

B. This is the same as case IIA except that the less capable searcher does a random search in cells which have not been searched, but which have some non-zero probability of containing the target.

C. Here both searchers do a random search (without overlap) in the region which must contain the target.

D. Here both searchers do a random search (without overlap) in the entire space.

E. In this case the commander directs the searchers to the areas least likely to contain the target, but which have some non-zero probability of containing the target.

These policies were chosen for examination because from experience the reader can intuitively rank them in order of increasing effectiveness. Policy II-E was included as an ultimate worst case, which it is.

Each control policy was implemented in each of 11 scenarios in which N, D, L_A and L_B are specified. In all scenarios $\alpha_A = 0.5$ and $\alpha_B = 1.0$. These scenarios span region A of Fig. 5.2, as indicated by the points on that figure.

A cycle of the program consists of the following steps:

1. On the basis of the information obtained in the preceding search, determine the entropy of the system at the end of the search.
2. Allow the target region to grow, (as indicated in the example), calculate the new location probability vector and obtain the new entropy of the system. Each searcher calculates his own location probability vector, and a third, based on the combined information, is calculated if the policy includes central control.
3. Based on the control policy, assign cells for each searcher to investigate.
4. Randomly move the target to a new position in accordance with the dodge variable D.
5. Search. If detection occurs, record the statistics and start a new run; otherwise, return to step 1 and continue.

A sufficient number of trials must be run for each policy and scenario to obtain reasonably good statistics. Most of the data reported here were obtained from runs of 500 replicas, but occasionally 1000 were obtained. The complete program is reproduced in Appendix A. Policy changes are made at the indicated location. The program is an example where central control is used. The local control program is somewhat simpler.

7. Results

As indicated in the previous section, the program generates a mass of data. In this context, the data serve to exercise the theory to ascertain whether the calculations coincide with our impression of the expected outcome for each policy.

The most primitive statistic to examine is the distribution of times to re-detection, see Fig. 7.1. Only three policies are included in this figure, but they are sufficient to demonstrate the results. The cases shown are CDF (Control Central Policy No. II.A), Local Control (Policy No. I.A) and Random Search (Policy No. I.B). Clearly the CDF dominates the other two at all timesteps for this scenario. In fact, it does for all scenarios, as one would expect. Note that the combination of all seven policies and 11 scenarios would generate 77 curves similar to those shown in Fig. 7.1.

We should comment that the average entropy at each timestep is not a particularly useful measure for the policies, see Fig. 7.2. (Here it appears that local control is better than central control at timestep 2.) It is somewhat surprising that this very primitive system mirrors an argument which is often debated in the operational forces. We will return to this point in the discussion.

Given the information contained in Fig. 7.1, a straightforward calculation determines the Markov transition probabilities, see Fig. 7.3, the stationary state probabilities, see Fig. 7.4, and from the stationary state probabilities and the state entropies, Fig. 7.2, the surveillance efficiencies, $\tilde{I}$.

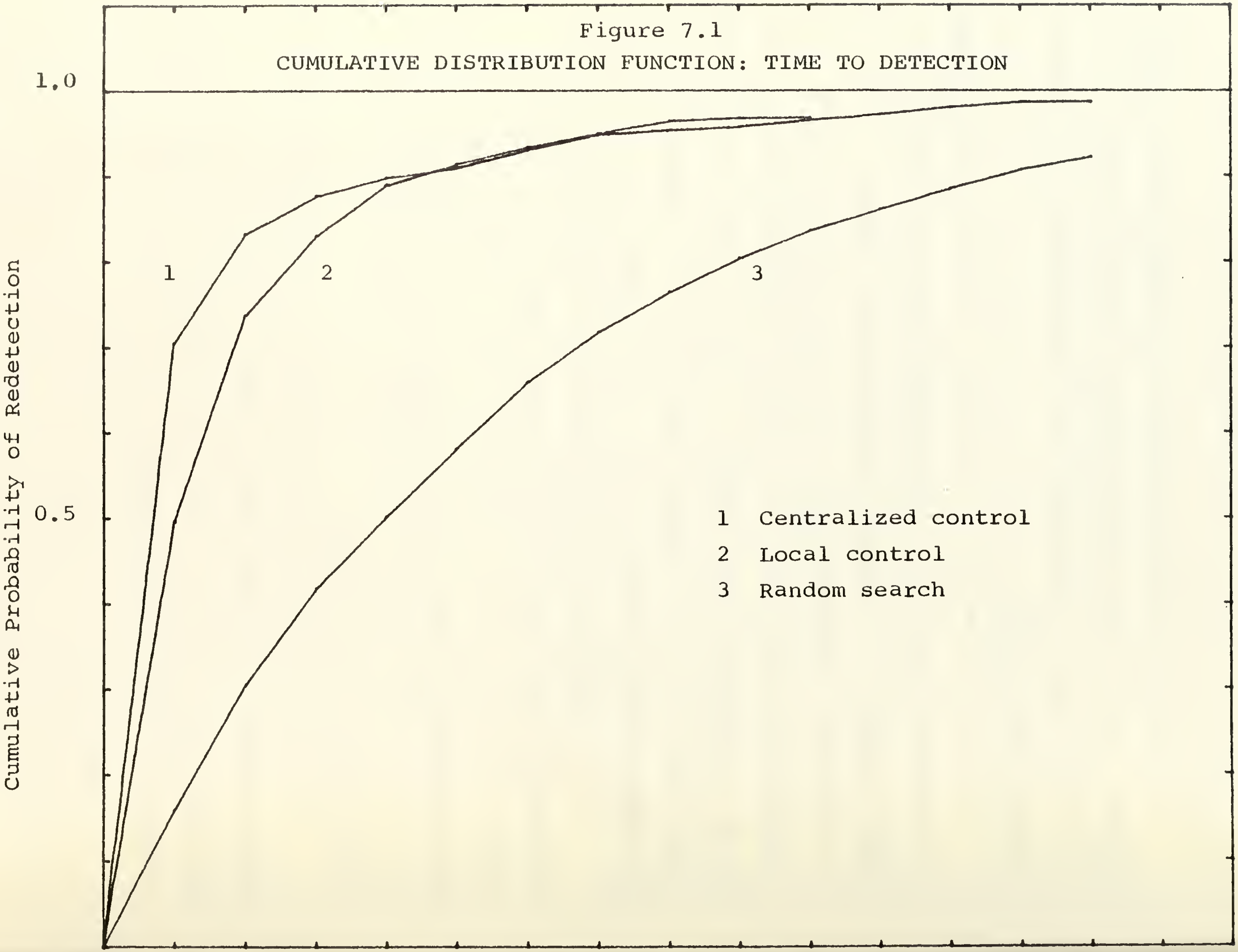

Figure 7.1

CUMULATIVE DISTRIBUTION FUNCTION: TIME TO DETECTION

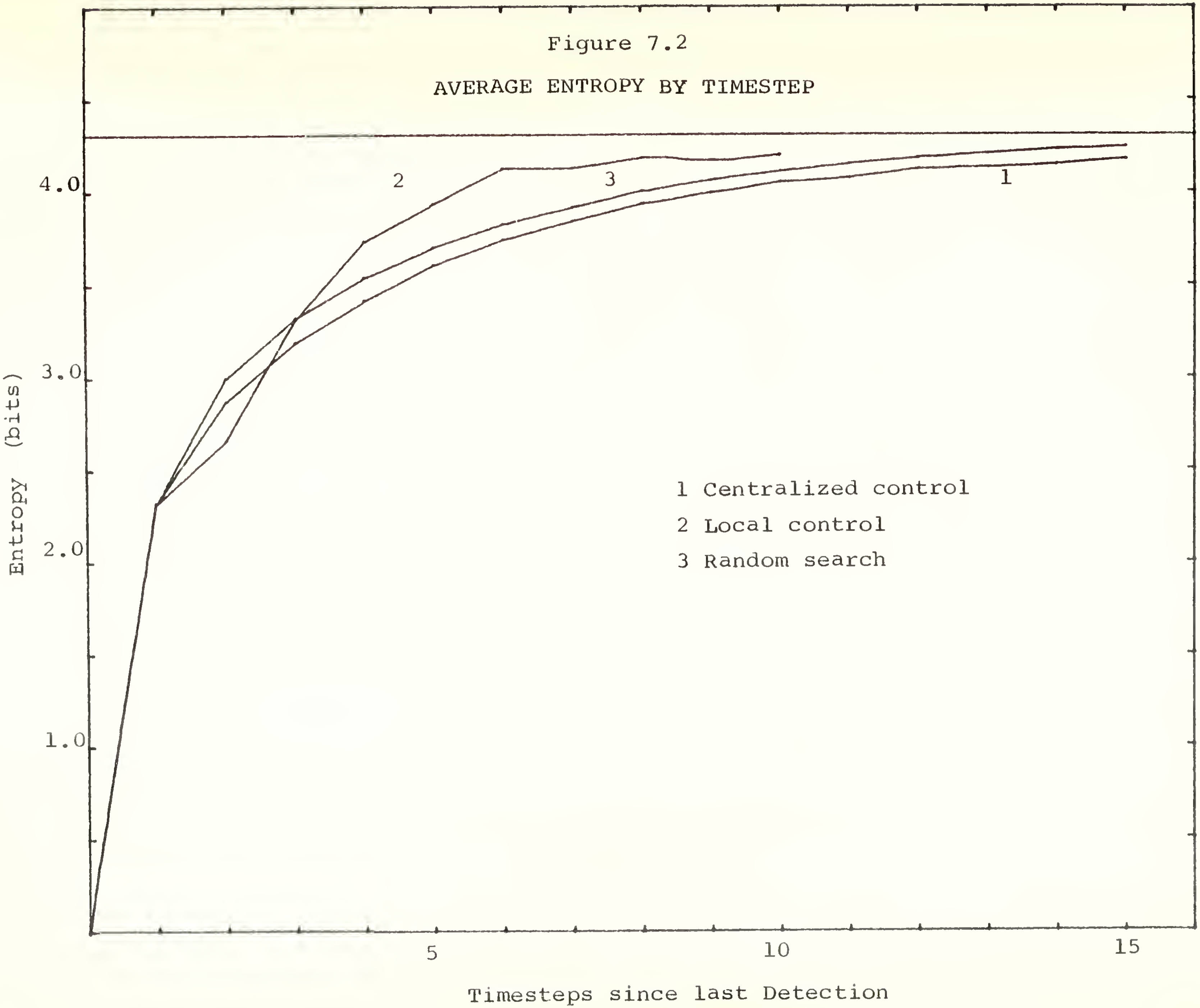

Figure 7.2

AVERAGE ENTROPY BY TIMESTEP

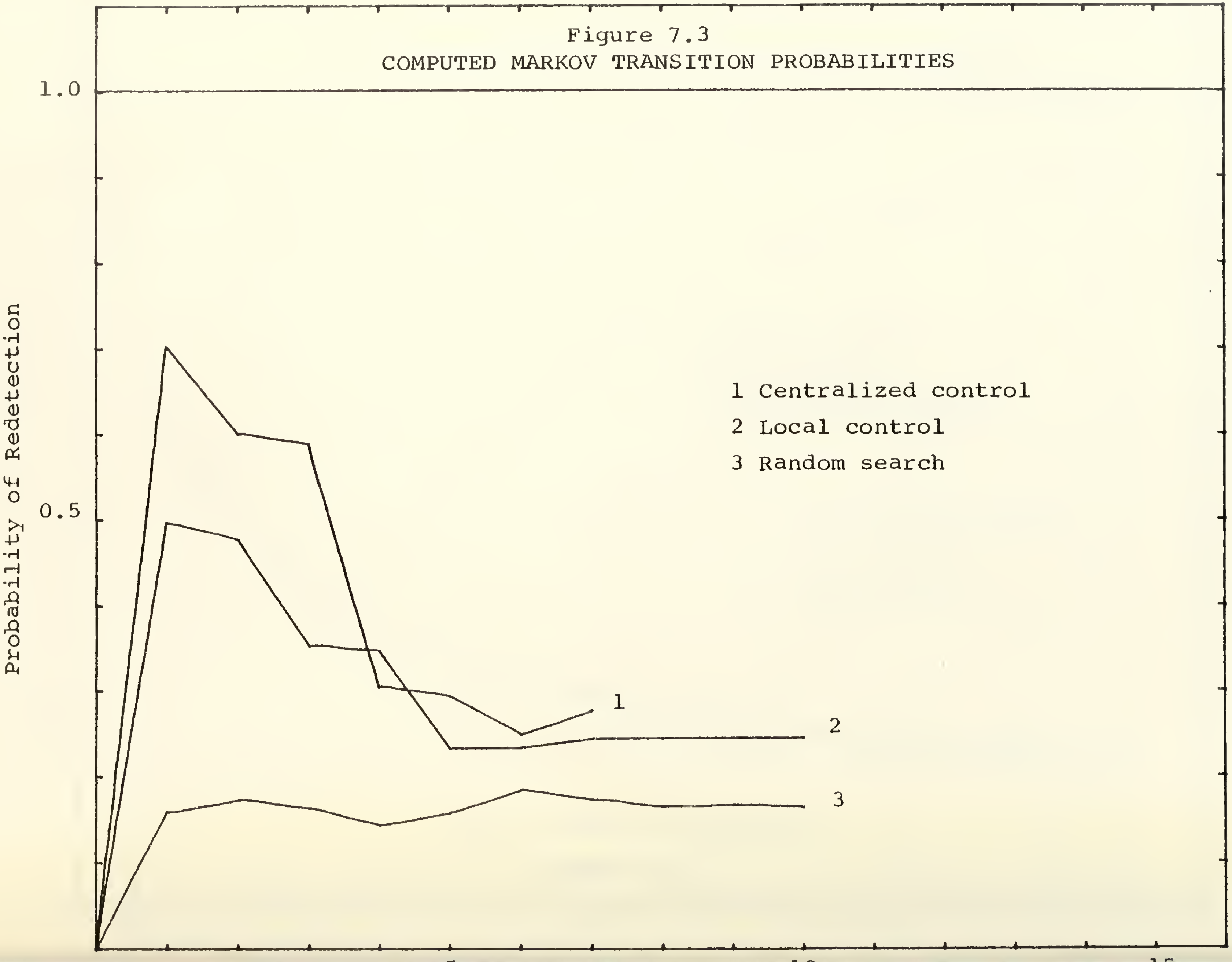

Figure 7.3
COMPUTED MARKOV TRANSITION PROBABILITIES

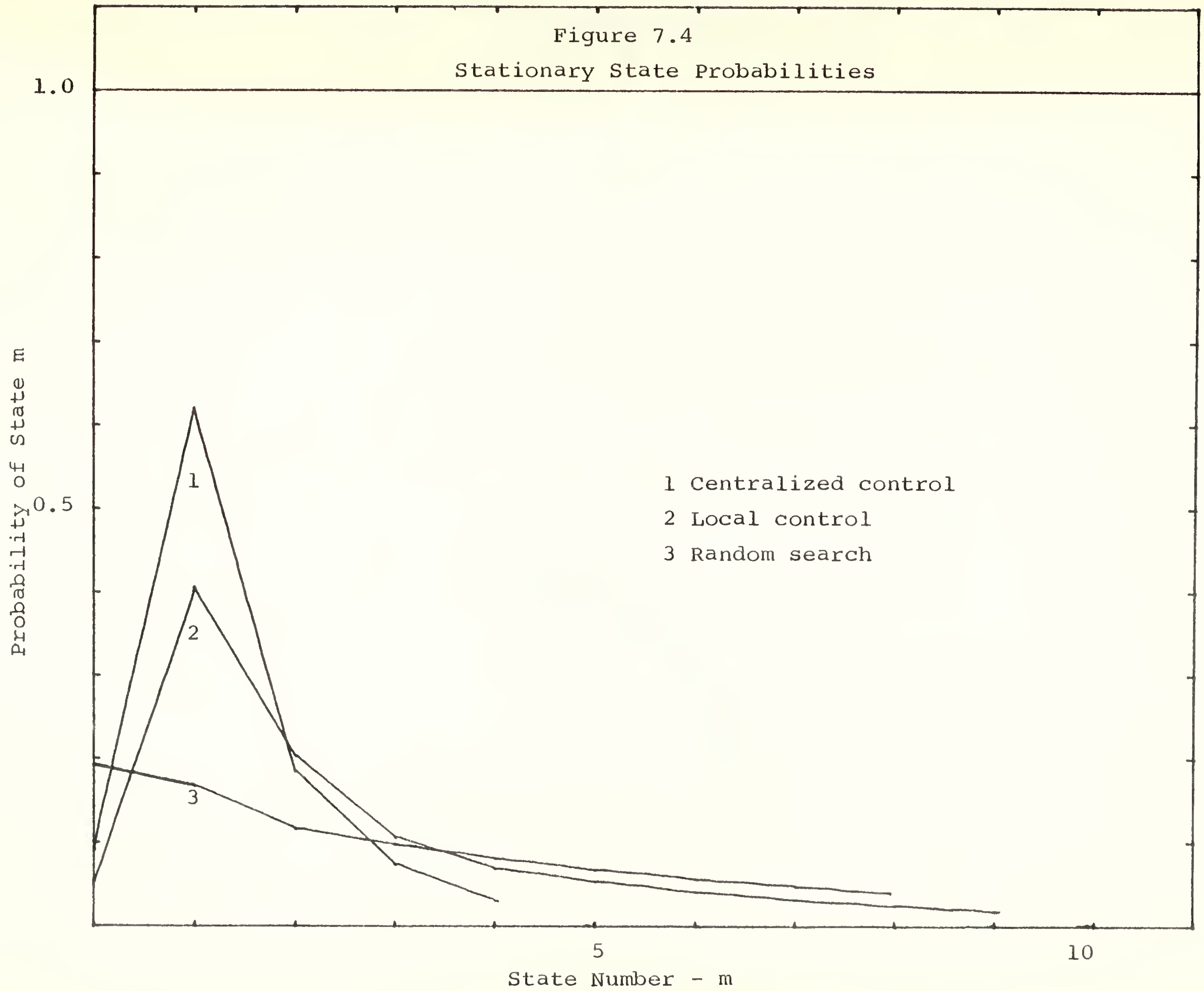
Figure 7.4
Stationary State Probabilities
1.0
0.5
Probability of State m
1
2
3
1 Centralized control
2 Local control
3 Random search
5
10
State Number - m

The set of values, referred to as a 'scenario' above, describes the size of the space (N), the dynamic capability of the target (D), and the detection capability (S) of the searchers by assigning a fixed number of assets to each. The relative capability of the target and the searchers can be varied over a broad range of values by adjusting these four numbers. The actual scenarios used in this study are listed in Table II. In all cases $\alpha_B = 1.0$, and usually $\alpha_A = 0.5$ (except in one scenario #11, $\alpha_A = 0.3$). These scenarios are rather widely dispersed over Region A, of the Surveillance Space; see Fig. 5.2.

The surveillance efficiencies for the eleven scenarios and the central control policy are plotted against the holding coefficient, (S/D*) in Fig. 7.5. Except near $\gamma_h = 1.0$, the efficiencies lie very closely along a straight line. The theory associates that line with the central control policy. The dotted line in Fig. 7.5 is the corresponding policy line for the random search policy (Policy I.B), see Fig. 7.6. Other policies are bounded by these two limiting cases, see Figs. 7.7 and 7.8. Note that local control is clearly always better than uncoordinated random search, but that a coordinated random search slightly dominates local control in all scenarios.

To summarize: the theory when applied to this simple model produces a unique number, the slope of the surveillance efficiency line, which is characteristic of the particular surveillance policy.

TABLE II

System Scenarios Examined

Scenario	N	D	L_A	L_B	α_A	α_B	γ_h
1	20	5	3	2	0.5	1.0	0.87
2	20	3	2	1	0.5	1.0	1.00
3	10	3	2	1	0.5	1.0	1.00
4	10	5	3	2	0.5	1.0	0.87
5	10	5	3	1	0.5	1.0	0.62
6	10	3	1	1	0.5	1.0	0.75
7	10	7	4	3	0.5	1.0	0.83
8	10	7	3	2	0.5	1.0	0.58
9	20	9	3	2	0.5	1.0	0.44
10	20	9	2	1	0.5	1.0	0.25
11	10	7	1	1	0.3	1.0	0.27

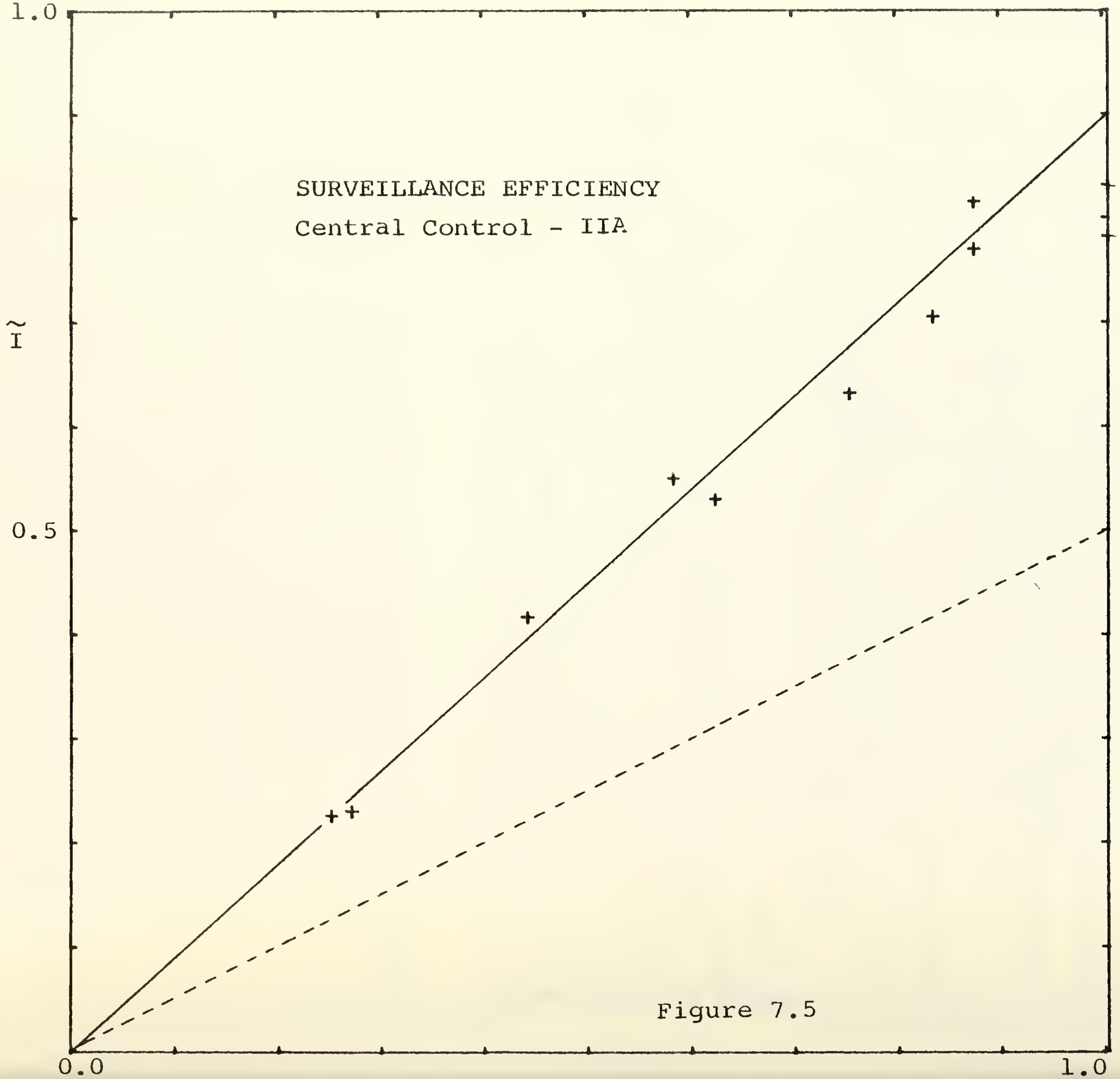
1.0
0.5
0.0
1.0
$\tilde{I}$
SURVEILLANCE EFFICIENCY
Central Control - IIA

Figure 7.5

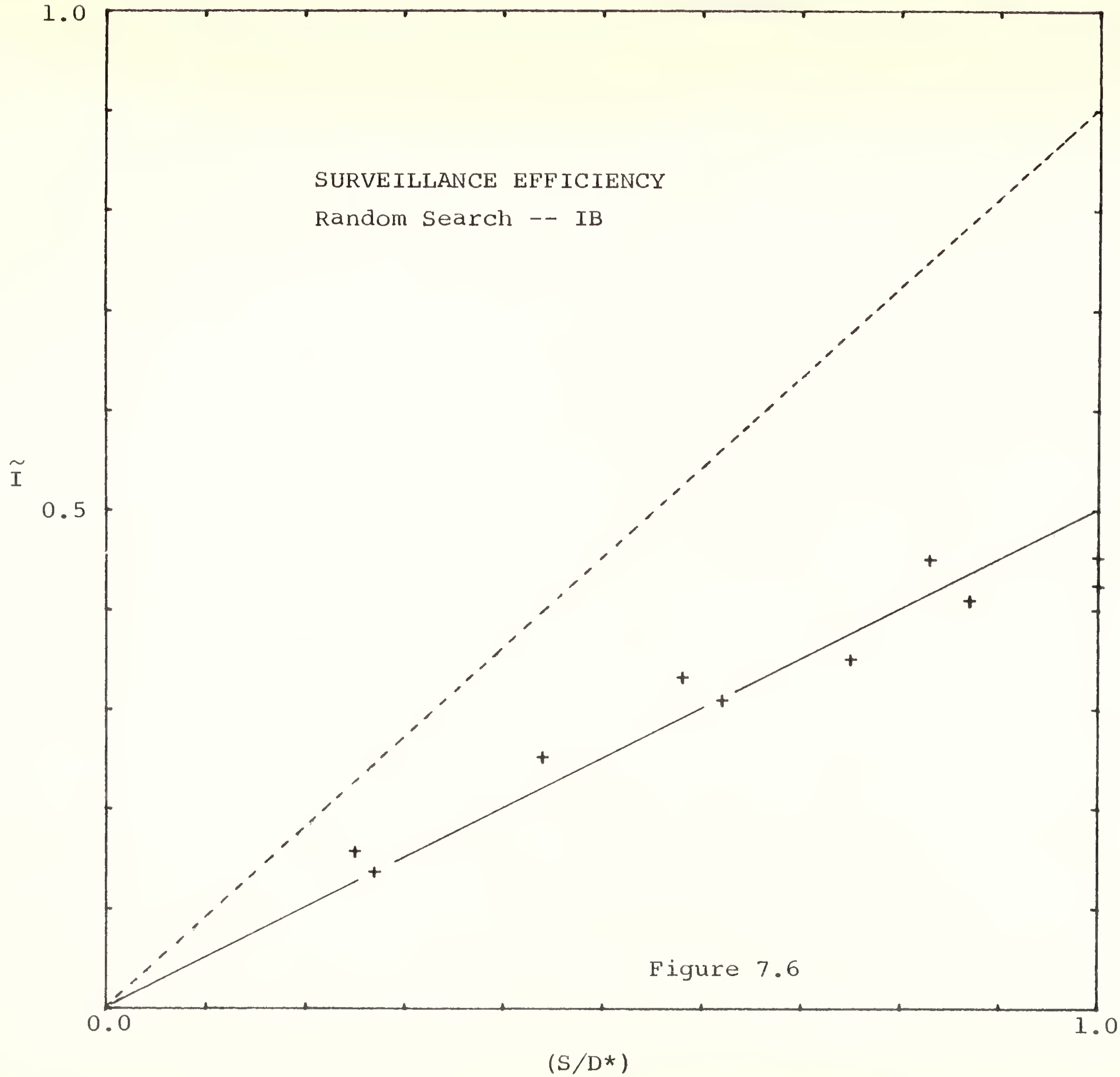
SURVEILLANCE EFFICIENCY
Random Search -- IB
1.0
0.5
0.0
1.0
$\tilde{I}$
(S/D*)

Figure 7.6

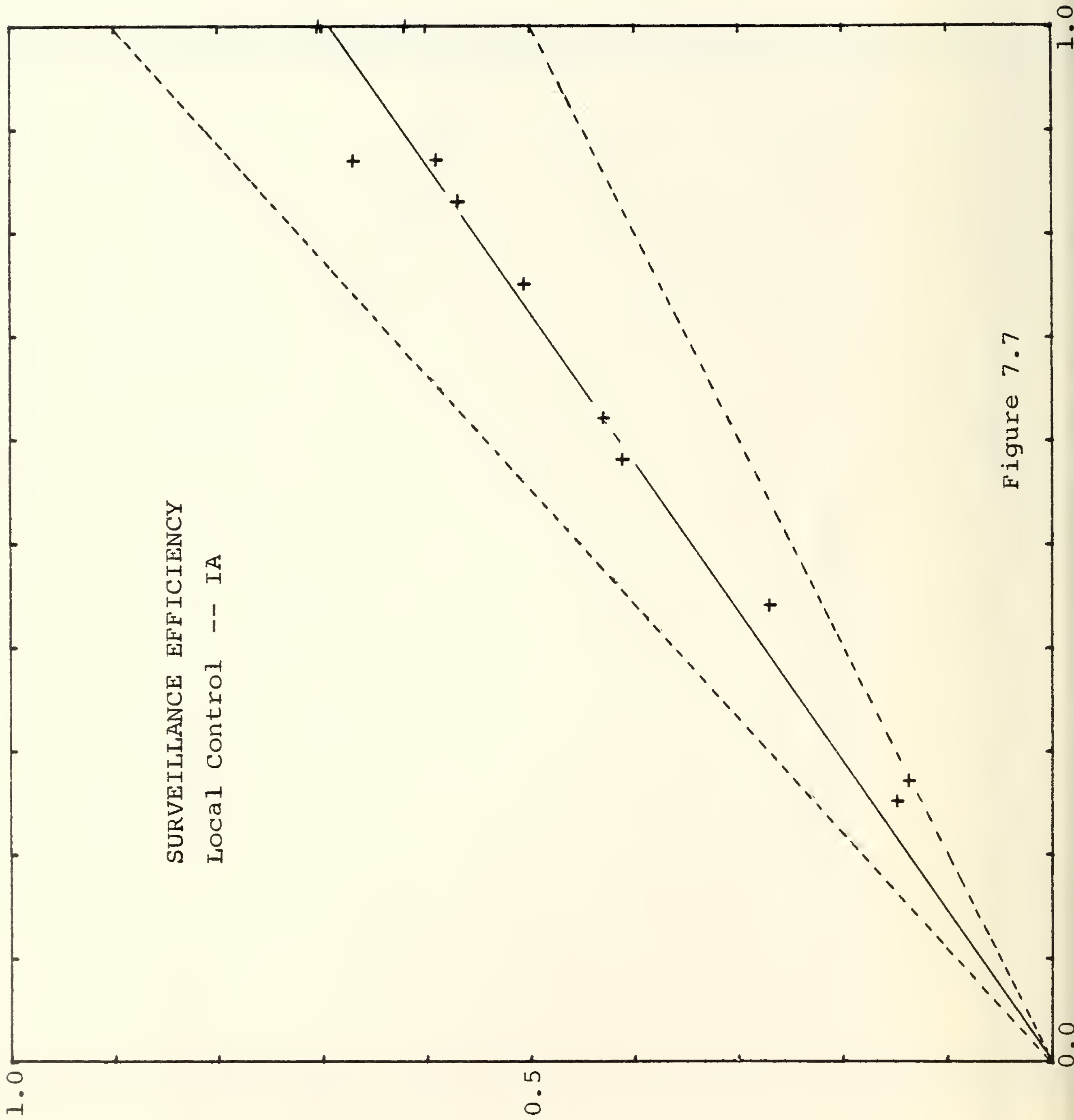

Figure 7.7

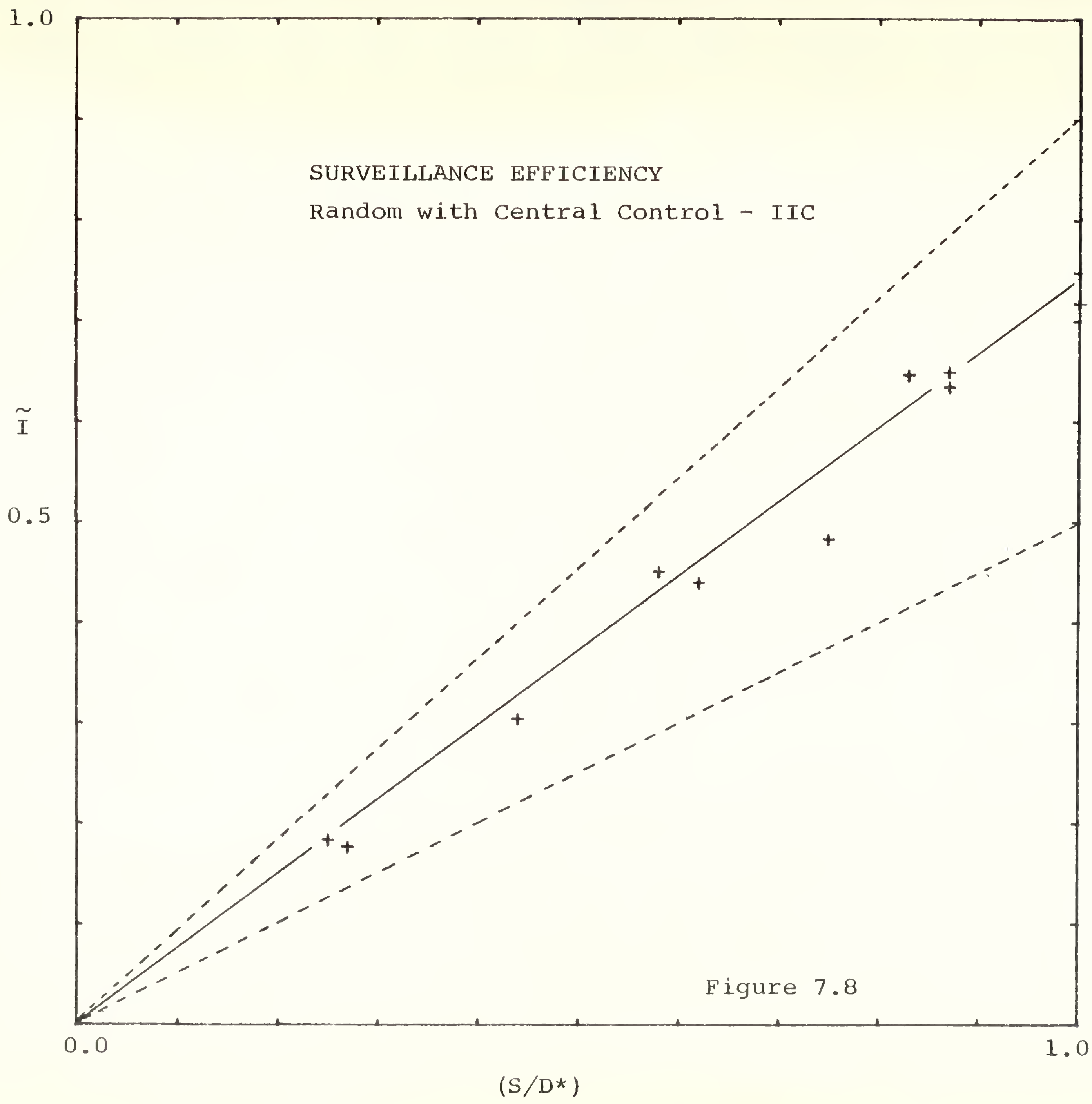
1.0
0.5
$\tilde{I}$
0.0
1.0
(S/D*)
SURVEILLANCE EFFICIENCY
Random with Central Control - IIC

Figure 7.8

8. Discussion and Conclusions

Although the computational model is extremely primitive it faithfully mirrors many real surveillance effects, and a surprising amount of surveillance lore can be extracted from it. The variables are unfamiliar, but they allow simple interpretations of complex real world phenomena.

The surveillance efficiency is a measure of effectiveness which codifies information about the present status of the system together with locational probabilities in such a way that it becomes possible to talk about the average, or steady state, status of the system under a given control policy. It successfully mirrors policy, not just the more directly measurable variables which describe the target and the searchers. These directly measurable variables are subsumed into the holding coefficient which quantifies the relative capabilities of the target and the searchers. Fig.s 7.5 to 7.8 clearly indicate that the holding coefficient, γ_h, fairly describes relative capabilities in the presence of a large number of policies.

A linear relationship between $\tilde{I}$ and γ_h holds very well except near the boundary between regions A and D of Surveillance Space (see Fig. 5.2). This is the boundary between Markovian and bi-stable behavior; it is not surprising that this simplified model fails at the transition. Examination of Figs. 7.5 to 7.8 clearly indicated that the failure is not policy dependent, although it is certainly more evident with some policies (IIA and IB) than with others (IA and IIC).

The individual data points do not lie exactly on the trend lines, but for stochastic results the deviations are minor for the relatively small samples considered. There is no evidence that the deviations are either policy or scenario sensitive. The policy ordering indicated in the figures is maintained <u>without exception</u> for every scenario. Certain scenarios were chosen to have the same holding coefficient, 1 and 4 and 2 and 3. The variations in surveillance efficiency between these pairs is our best measure of the reproducibility of the results.

The parameters normally associated with a surveillance process are buried in the holding parameter. Additional search assets, or better performance of existing assets (increased α_x) appear as an increase in S and hence in γ_h. Note that the model suggests that the same assets deployed on additional platforms will not increase performance unless a larger number of cells can be investigated in a given epoch. The model distinguishes between the number of assets, L_x, and the performance of each asset, α_x. For constant α_x, an increased search speed would be modeled as an increased L_x, that is, larger area searched.

The revisit interval and target speed are described by D. If the revisit time is long, the target has a longer time in which to move, and D is correspondingly increased. Similarly, if the target speed were increased, D should increase to indicate that the area which must be searched has increased. This area, and hence D, should go as $(\text{speed})^2$.

The model reinforces our intuition in several respects. Fig. 8.1 gives an example of the effects created by moving between two policy lines. Suppose that a surveillance system is operating at point A ($\tilde{I} = 0.3$, with $\gamma_h = 0.6$). The commander has two options: either he can change to another policy, point B, which retains the same efficiency at a reduced cost ($\gamma_h = 0.34$) or, if the same assets are deployed the efficiency can be increased to 0.53 by a change in policy. Depending on the mission either the re-deployment of assets, point B, or the improved efficiency, point C, would be appropriate, but clearly, he should not operate at A. The model

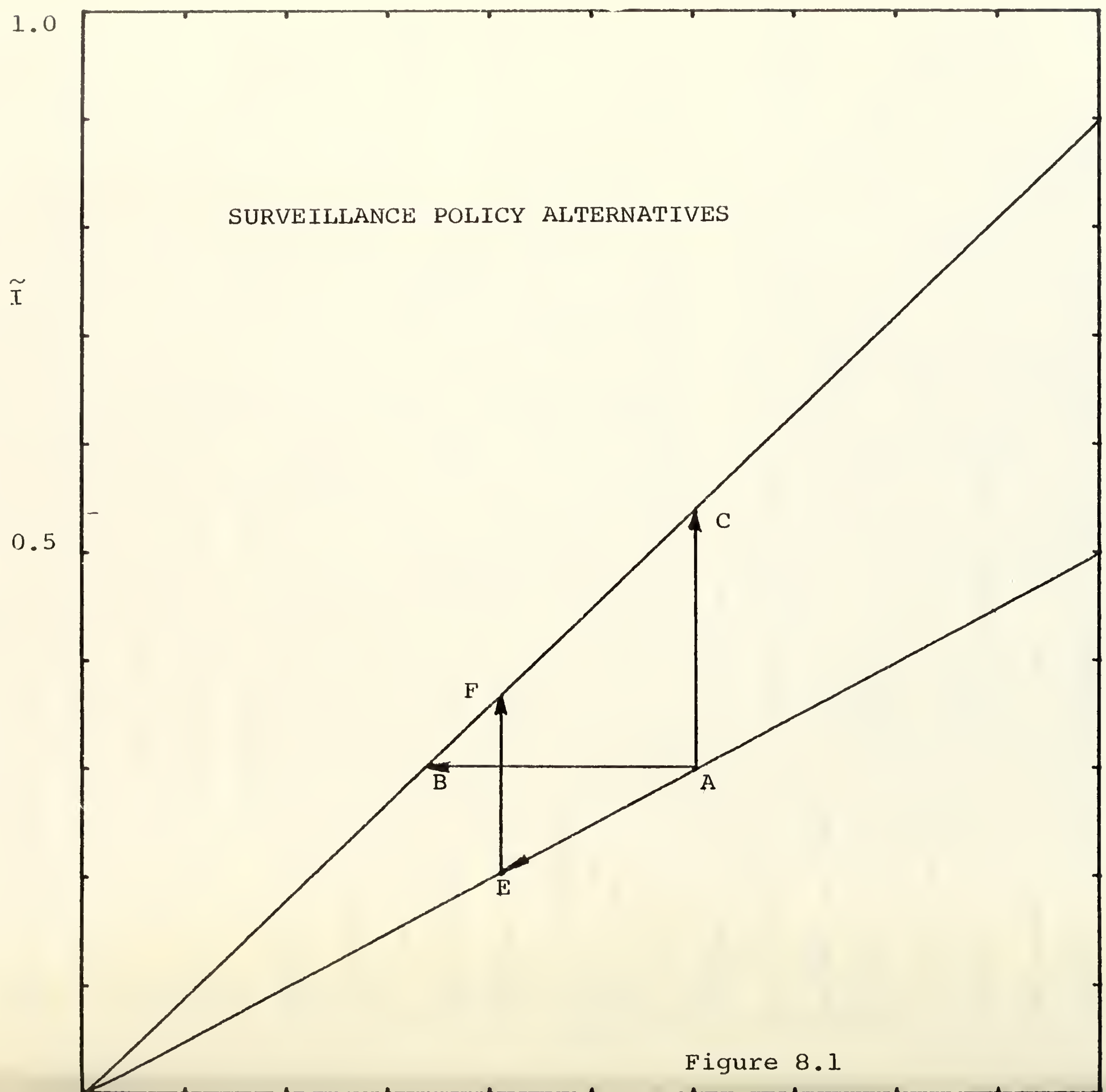

Figure 8.1

shows how effort expended to improve control policy can be traded for effort expended to improve sensors.

Even more subtle ideas can be interpreted from these results. The effect of increased "time-late-on-target" must be interpreted as an increase in D (the target has more time to dodge) and point E indicates the new efficiency. Time-late can be traded-off with increased assets (stay at point A by increasing S) or by policy improvements, the move to point F. Communications delays also increase D and can be traded-off in the same way.

The results we have presented in this paper so far suggest that a great deal can be learned from a relatively simple model of a two-level military decision-making system. The application to the problem of surveillance C^3 made the choice of entropy as a fundamental measure of performance obvious. We believe that entropy plays a central role in the characterization of many other military C^3I systems too. There remain, however, a number of important issues regarding the application at hand, surveillance C^3.

An important model extension concerns characterization of the target environment. To summarize, the present simulation treats a single target moving randomly in a one-dimensional closed space. Furthermore, no coupling has been allowed between the Actions of the Surveillance Commanders and the target's motions. We should like to treat a variable number of target objects moving in a two-dimensional space which has absorbing and emitting walls (targets allowed to exit and enter the space). Furthermore, in practice target objects may belong to different species; the locational certainty of the species may be of unequal value to the surveillance commanders. Sensors may identify the species (surveillance report contain location and classification information) or not (reports contain location information only). The target's dynamic behavior may not be purely random and may, in fact, be coupled to the movement of, or proximity to, the sensors. These ramifications can, and should be, studied within the framework of the cybernetic model used here.

Another dimension relates to the characterization of the surveillance sensors themselves. False alarm probabilities were included in the definition of the sensor transfer function, but in the computer simulations they were set to zero. A study of the effect of a significant number of false alarms, accompanied by a correspondingly appropriate increase in detection probability on overall system performance is definitely warranted. The question: "Would allowing more false alarms, in order to get more detections, materially affect overall system performance and, if so, in what way?", needs to be answered even for several of today's operational systems. It seems that further exploration of this dimension of our model may be very useful in that regard.

A third dimension to be explored is the overall complexity of the organizational structure. Only a two-level system has been modeled. (A tertiaray level, the sensor commanders, has been included implicitly.) The computer simulation results are for only two, infimal level commanders. Additional fractionization of the infimal level may be important, however, we would expect the system performance always to fall between the best case of centralized, optimum control (Fig. 7.5, Policy IIA), and the worst case of fixed distributed sensors with no control (Fig. 7.6, Policy IB). Adding additional operational levels of overall system organization only seems reasonable if the goals and/or environment of the model are enriched. Some benefits may be derived by explicitly including the behavior of indiviudal sensor commanders. To do this requires they be given goals and decision making capacity. In general, lower level commander's decision alternatives are more specialized and detailed than their superiors. Again, a richer model will result by their inclusion.

Finally, it seems certain that additional information is embedded in the entropy random process, H(t). In particular the average rate of fluctuation of H(t) is believe, based on a statistical mechanics analog, to embody a measure of "internal information flow". If so, this is extremely important. It will allow the internal informational and decision making complexity of a system to be characterized by an observable, macroscopic system variable.

One can also imagine a control policy based on a real time estimate of H(t). A commander may wish to reduce locational uncertainty below some critical threshold during an important time interval so that an action may occur elsewhere in the system, such as the launching of aircraft, movement of troops, etc. Thus, we can imagine resources being allocated in accordance with a more complicated goal description than that investigated here. Further research into specifying the goals or objective functions of the commanders appears warranted and will enrich the model as well as our understanding of the processes of C^3 as a whole.

Further investigation of the analogy between cybernetic, system dynamic models and statistical thermodynamic models appears to be an exciting and promising avenue for further research.

APPENDIX A

```
      WRITE(6,9652)
 9652 FORMAT(//,'   ENTROPY DISTRIBUTION (DELTA H TO 0.1) :',//)
      WRITE(6,9654) (HLAB(I),LTAL(I),I=1,IHMAX)
 9654 FORMAT(10(F6.1,I4),/)
      WRITE(6,9657)
 9657 FORMAT(/,'  DISTRIBUTION OF AVERAGE ENTROPY BY TIMESTEP:',/)
      WRITE(6,9659) (I,AVH(I),I=1,ITMAX)
 9659 FORMAT(10(I5,F7.3),/)
      WRITE(6,9672)
 9672 FORMAT(/,'   DISTRIBUTION OF MARKOV PROBABILITIES BY TIMESTEP:',/)
      WRITE(6,9659) (I,PEND(I),I=1,ITMAX)
      WRITE(6,9653)
 9653 FORMAT(//////)
      GO TO 10
 9999 STOP
      END
      SUBROUTINE GGUB(ISEED,N,R)
C
C                                         D2P31M = (2**31) - 1
C                                         D2PN31 = 1 / (2**31)
      DIMENSION          R(1)
      DOUBLE PRECISION   Z,D2P31M,D2PN31,DMOD
      DATA               D2P31M/2147483647.D0/,D2PN31/Z3920000000000000/
      Z = ISEED
      DO 5 I=1,N
         Z = DMOD(16807.D0*Z,D2P31M)
    5 R(I) = Z * D2PN31
      ISEED = Z
      RETURN
      END
```

```
C
C          TERMINATE THE RUN
C
 5000 CONTINUE
      NRUN=NRUN-1
      WRITE(6,9601) IHEAD
      WRITE(6,9510) I3,NRM,PMIN,PDA,PDB,LOCMAX,ISPC,[illegible]
      WRITE(6,9650) NRUN,NSA,NSB,NLOST
 9650 FORMAT(///'   RESULTS FOR',I6,' RUNS:  A LOCATED',I5,' [illegible]',
     X          I5,' TIMES, AND',I5,' WERE LOST',//,
     X          ' DISTRIBUTION OF TIMES TO LOCATE IS:',//)
      WRITE(6,9651)  (I,ITAL(I),I=1,ITMAX)
 9651 FORMAT(10(I6,I4),/)
      DHLAB=0.1
      HLAB(1)=0.0
      DO 5100 I=2,IHMAX
      HLAB(I)=HLAB(I-1)+DHLAB
 5100 CONTINUE
      FNRM=1.0/FLOAT(NRM)
      TTOT=0.0
      FNON=NRUN
      DO 5200 I=1,ITMAX
      IF(NTALH(I).EQ.0) GO TO 5130
      FD=NTALH(I)
      AVH(I)=AVH(I)/FD
 5130 CONTINUE
      FD=ITAL(I)
      TTOT=TTOT+FD
      CH(I)=TTOT*FNRM
      FIT=ITAL(I)
      IF(FNON.LT.1.0E-1)    GO TO 5150
      PEML(I)=FIT/FNON
      PMN(I)=(FNON-FIT)/FNON
      FNON=FNON-FIT
      GO TO 5200
 5150 CONTINUE
      PEML(I)=1.0
      PMN(I)=0.0
 5200 CONTINUE
      WRITE(6,9653)
 9653 FORMAT(/,'  CUMULATIVE DISTRIBUTION [illegible]:',/)
      WRITE(6,9659) (I,CH(I),I=1,ITMAX)
      WRITE(6,9655)
 9655 FORMAT(//,'  DISTRIBUTION OF TIMES [illegible]:',/)
      WRITE(6,9651) (I,[illegible](I),I=1,ITMAX)
      WRITE(6,9656)
 9656 FORMAT(//,' [illegible]:',/)
      WRITE(6,9651) (I,[illegible](I),I=1,ITMAX)
```

```
 3100 CONTINUE
      IF(IP.EQ.1) WRITE(6,9630) NRUN,IH,K
 9630 FORMAT(I10,I15,I6)
      GO TO 100
C
C        REGAINED CONTACT:  RECORD SUCCESS AND REPEAT
C
C
C        A MAKES THE DETECTION
C
 4000 CONTINUE
      ITALA(IT)=ITALA(IT)+1
      IF(IT.GT.ITAMAX) ITAMAX=IT
      ITAL(IT)=ITAL(IT)+1
      IF(IT.GT.ITMAX) ITMAX=IT
      IH=10.0*HNEW+1
      LTAL(IH)=LTAL(IH)+1
      IF(IH.GT.IHMAX) IHMAX=IH
      NSA=NSA+1
      IF(IP.EQ.1) WRITE(6,9640) NRUN,IT,IMAX
 9640 FORMAT(' RUN NUMBER:',I5,' SEARCHER A RELOCATED TARGET AT TS',
     X       I3,' WHEN THERE WERE',I3,' POSSIBLE LOCATIONS',///)
      NRUN=NRUN+1
      IF(NRUN.GT.NRM) GO TO 5000
      IF((NRUN/20)*20.EQ.NRUN)  WRITE(6,3338) NRUN,K,NSA,NSB
 3338 FORMAT(I10,I15,2I5)
      IF(K.GT.4500) GO TO 3100
      GO TO 500
C
C        B MAKES THE DETECTION
C
 4200 CONTINUE
      ITAL(IT)=ITAL(IT)+1
      IF(IT.GT.ITMAX) ITMAX=IT
      ITALB(IT)=ITALB(IT)+1
      IF(IT.GT.ITBMAX) ITBMAX=IT
      IH=10.0*HNEW+1
      LTAL(IH)=LTAL(IH)+1
      IF(IH.GT.IHMAX) IHMAX=IH
      NSB=NSB+1
      IF(IP.EQ.1) WRITE(6,9641) NRUN,IT,IMAX
 9641 FORMAT(' RUN NUMBER:',I5,' SEARCHER B RELOCATED TARGET AT TS',
     X       I3,' WHEN THERE WERE',I3,' POSSIBLE LOCATIONS',///)
      NRUN=NRUN+1
      IF(NRUN.GT.NRM) GO TO 5000
      IF((NRUN/20)*20.EQ.NRUN)  WRITE(6,3338) NRUN,K,NSA,NSB
      IF(K.GT.4500) GO TO 3100
      GO TO 500
```

```
      NA=NA-4
      GO TO 2400
 2309 CONTINUE
      NA=NA+4
      GO TO 2400
 2310 CONTINUE
      NA=NA+5
      GO TO 2400
 2311 CONTINUE
      NA=NA-5
 2400 CONTINUE
      IF(NA.GT.LOCMAX) NA=NA-LMP
      IF(NA.LT.0)      NA=NA+LMP
 2500 CONTINUE
      IF(IP.EQ.1) WRITE(6,9660) IT,NA
 9660 FORMAT('  TIMESTEP',I3,' TARGET AT LOCATION',I5)
      IF(LLMA.EQ.0) GO TO 2510
      IF(IP.EQ.1) WRITE(6,9662) (LOOK(L),L=1,LLMA)
 9662 FORMAT(35X,' A WILL LOOK IN:',20I3,//)
 2510 CONTINUE
      IF(LLMB.EQ.0) GO TO 1500
      IF(IP.EQ.1.AND.IT.GE.ITB) WRITE(6,9661) (LOOKB(L),L=1,LLMB)
 9661 FORMAT(35X,' B WILL LOOK IN:',10I3,//)
      GO TO 1500

         LOGIC FAILURE

 2000 CONTINUE
      WRITE(6,9670) IT,LMP,LLMA,LLMB,IMAX
 9670 FORMAT(//,'  LOGIC FAILED ON NRUN =',I5,' WITH LMP =',I5,
     X      ', SEARCHER A LOOK SPACE OF',I4,/,'  SEARCHER B LOOK SPACE'
     X,' OF',I4,', AND DODGE SPACE OF',I4,//)

         CONTACT HAS BEEN LOST:  RECORD FAILURE AND RESTART

 3000 CONTINUE
      NLOST=NLOST+1
      LLP1=LLMA+LLMB
      IF(IP.EQ.1) WRITE(6,9620) NRUN,NA,LLP1,(LOOK(I),I=1,LLMA),
     X                          (LOOKB(I),I=1,LLMB)
 9620 FORMAT('  RUN NUMBER:',I5,' FAILED TO HOLD TARGET LOCATED AT',I5,
     X      '.  THERE WERE ',I3,' POSSIBILITIES, LOOKED AT',10I3,/,  ,/)
      NRUN=NRUN+1
      ITAL(IT)=ITAL(IT)+1
      IF(IT.GT.ITMAX) ITMAX=IT
      IF(NRUN.GT.NR 1) GO TO 5000
      IF(N.GT.4501) GO TO 
      GO TO 100
```

```
2015 FORMAT('  ENTROPY FOR THE NEW LOCATIONS IS',F10.5,/)
C
C        IMAX IS NOW THE NUMBER OF POSSIBLE LOCATIONS
C
C        THIS IS THE COORDINATED SEARCH LOGIC
C
2000 CONTINUE
     IF(IT.LT.ITR) GO TO 2100
     DO 2090 L=1,LLMB
     LOCKB(L)=NLOC(L)
2090 CONTINUE
2100 CONTINUE
     DO 2190 L=1,LLMA
     LOCK(L)=NLOC(LLMB+L)
     LOCA(L)=LOCB(LLMB+L)
2190 CONTINUE
2200 CONTINUE
C
C
C
C        MOVE TARGET
C
2300 CONTINUE
     K=K+1
     M=ISPC*RAN(K)+1
     GO TO (2301,2302,2303,2304,2305,2306,2307,2308,2309,2310,2311),M
2301 CONTINUE
     NA=LA
     GO TO 2400
2302 CONTINUE
     NA=NA-1
     GO TO 2400
2303 CONTINUE
     NA=NA+1
     GO TO 2400
2304 CONTINUE
     NA=NA-2
     GO TO 2400
2305 CONTINUE
     NA=NA+2
     GO TO 2400
2306 CONTINUE
     NA=NA+3
     GO TO 2400
2307 CONTINUE
     NA=NA-3
     GO TO 2400
2308 CONTINUE
```

```
      PROB(IMAX)=TPROB(N)
      NPEX(IMAX)=0
      GO TO 1900
 1850 CONTINUE
      PROB(I)=PROB(I)+TPROB(N)
 1900 CONTINUE
      IF(IMAX.GT.LMP) GO TO 2600
C
C         MAKE & TALLY ENTROPY
C         ORDER BY PROBABILITIES:   .LT. = LOW TO HIGH; .GT. = HIGH TO LOW
C
 1910 CONTINUE
      IF(LMA.GT.IMAX) LMA=IMAX
      IF(LMB.GT.IMAX) LMB=IMAX
      H=0.0
      MMAX=1
      DO 1950 I=1,IMAX
      LOCB(I)=I
      NLOC(I)=LOC(I)
      TPROB(I)=PROB(I)
      IF(PROB(I).GT.PROB(MMAX)) MMAX=I
      IF(PROB(I).LT.1.0E-6) GO TO 1950
      H=H+PROB(I)*ALOG(1.0/PROB(I))
 1950 CONTINUE
      HNEW=H*BLNR
      AVH(IT)=AVH(IT)+HNEW
      NTALH(IT)=NTALH(IT)+1

      IMM=IMAX-1
      DO 1970 I=1,IMM
      JMAX=IMAX-I
      DO 1960 J=1,JMAX
      IF(TPROB(J).GE.TPROB(J+1)) GO TO 1960
      TEMP=TPROB(J)
      TPROB(J)=TPROB(J+1)
      TPROB(J+1)=TEMP
      TEMP=NLOC(J)
      NLOC(J)=NLOC(J+1)
      NLOC(J+1)=TEMP
      TEMP=LOCB(J)
      LOCB(J)=LOCB(J+1)
      LOCB(J+1)=TEMP
 1960 CONTINUE
 1970 CONTINUE
      IF(IP.EQ.1) WRITE(6,6011) (LOC(I),PROB(I),I=1,IMAX)
      IF(IP.EQ.1) WRITE(6,6011) (NLOC(I),TPROB(I),I=1,IMM)
 6011 FORMAT(/,' LOC ... AND PROBABILITIES ...:',10(...))
      IF(IP.EQ.1) WRITE(6,6013) HNEW
```

```
      DO 1600 I=1,IMAX
      IF(PROB(I).LE.PMIN) GO TO 1600
      M=M+1
      LOC(M)=LOC(I)
      PROB(M)=PROB(I)
      NPEX(M)=0
 1600 CONTINUE
 1610 CONTINUE
C
C        NEW TIMESTEP & TEST FOR TERMINATION
C
      IT=IT+1
      IF(IT.GT.ITMMM) GO TO 3000
      LLMA=LMA
      LLMB=LMB
C
C        EXPAND THE SEARCH AREA
C
      IMAXL=M
      NMAX=IMAXL*ISPC
      M=0
      TRANS=1.0/FISPC
      DO 1700 I=1,IMAXL
      NST=LOC(I)-(ISPC/2+1)
      DO 1650 J=1,ISPC
      NST=NST+1
      M=M+1
      NLOC(M)=NST
      IF(NLOC(M).GT.LOCMAX) NLOC(M)=NLOC(M)-LMP
      IF(NLOC(M).LT.0)      NLOC(M)=NLOC(M)+LMP
      TPROB(M)=PROB(I)*TRANS
 1650 CONTINUE
 1700 CONTINUE
      DO 1750 J=1,ISPC
      NPEX(J)=0
      LOC(J)=NLOC(J)
      PROB(J)=TPROB(J)
 1750 CONTINUE
      IMAX=ISPC
      IF(NMAX.EQ.ISPC) GO TO 1910
      ISP=ISPC+1
      DO 1900 N=ISP,NMAX
       ITM=IMAX
      DO 1800 I=1,ITM
      IF(LOC(I).EQ.NLOC(N)) GO TO 1850
 1800 CONTINUE
      IMAX=IMAX+1
      LOC(IMAX)=NLOC(N)
```

```
      IF(LH[illegible]. [illegible]. )[illegible] 1525
      DO 1540 I=1,IL[illegible]
      IF(PROB(L). [illegible]. [illegible]) GO TO 15[illegible]
      K=K+1
      IF(RAN(K).LE.P[illegible]) GO TO [illegible]
 15[illegible] CONTINUE
      M=LOCA(L)
      NPLA( )=-1
      P[illegible]( )=[illegible]
 1540 CONTINUE
 1525 CONTINUE
      IF(L[illegible]. 0.0) GO TO 1550
      DO 1520 L=1,IL[illegible]
      IF(L[illegible](L).[illegible].[illegible]) GO TO 1510
      K=K+1
      IF(RAN(K).LE.PE3) GO TO 4200
 1510 CONTINUE
      M=LOCA(L)
      PROB(M)=PROB(M)*QB
      NPEX(M)=-1
 1520 CONTINUE
 1550 CONTINUE
C
C        CALCULATE NEW PROBABILITIES FOR OLD LOCATIONS
C
      P=0.0
      DO 1570 I=1,IMAX
      P=P+PROB(I)
 1570 CONTINUE
      RAT=1.0/P
      H=0.0
      DO 1580 I=1,IMAX
      PROB(I)=RAT*PROB(I)
      IF(PROB(I).LT.1.0E-6) GO TO 1580
      H=H+PROB(I)*ALOG(1.)/PROB(I))
 1580 CONTINUE
      HOLD=H*ELN[illegible]
C
C        PRINT NEW PROBABILITIES FOR OLD LOCATIONS
C
 1590 CONTINUE
      IF(IP.EQ.1) WRITE(6,9011) (LOC(I),PROB(I),I=1,IMAX)
      IF(IP.EQ.1) WRITE(6,9012) HOLD
 9012 FORMAT('  ENTROPY FOR THE OLD LOCATIONS IS',F10.3,//)
C
C        EXPAND SEARCH AREA AND CALCULATE PROBABILITIES
C
      M=0
```

```
      LCMP=LMP
      FLCCM=FLOAT(K)
      BLN=0.69314718
      BLNR=1.0/BLN
      LRMAX=ALOG(10.0)*BLNR
      DO 20 I=1,100
      ITAL(I)=0
      LTAL(I)=0
      HLAB(I)=0.0
      ITALA(I)=0
      ITALB(I)=0
      NTALH(I)=0
      AVH(I)=0.0
      CH(I)=0.0
   20 CONTINUE
  100 CONTINUE
      CALL GGUB(IF,5000,RAN)
      DO 200 I=1,5000
      IRAN(I)=FLCCM*RAN(I)
  200 CONTINUE
      K=0
C
C         START A REPLICA
C
  500 CONTINUE
      IMAX=1
      PROBT=0.0
      IF(IP.EQ.1) WRITE(6,9621) NRUN
 9621 FORMAT(////,'   RUN NUMBER',I5,//)
C
      IT=0
      K=K+1
      NA=LMP*RAN(K)
      DO 1010 I=1,LMP
      PROB(I)=0.0
      NPEX(I)=0
 1010 CONTINUE
C
      LOC(1)=NA
      PROB(1)=1.0
      IT=0
      N=1
      GO TO 1610
C
C         SEARCH WHEN DETECTION HAS ALREADY BEEN MADE
C
 1500 CONTINUE
      IF(IT.LT.ITR) GO TO 1525
```

```
C
C        THIS MODEL COORDINATES THE SEARCH POLICY
C
C
C        MA          TARGET LOCATION
C        LOC(I)      POSSIBLE TARGET LOCATIONS
C        LPOC(I)     POTENTIAL TARGET LOCATIONS
C
      DIMENSION LOOK(20),LOOKB(20),THEAD(20)
      DIMENSION LOC(50),LOCA(50),LOCB(50),NPEX(50),P  (5 )
      DIMENSION ITALA(100),ITALB(100),AVH(100),NTALH(100),C H(100)
      DIMENSION HLAB(100),LTAL(100),ITAL(100),      (100),    (100)
      DIMENSION NLOC(500),TPROB(500)
      DIMENSION  RAT(5000),TRAN(5000)
      READ(5,9500) THEAD
 9500 FORMAT(20A4)
      ITMMM=15
   10 CONTINUE
      READ (5,9510) IR,NEM,PMIN,PDA,PDB,LOCMAX,ISPC,LMA,LMB,ITR,IP
 9510 FORMAT(1X,I14,I5,3F5.2,11I5)
      IF(IR.LE.0) GO TO 9999
      WRITE(6,9601) THEAD
 9601 FORMAT(1H1,10X,20A4,//,'          SEED    RUNS PMIN PDA   PDB ',
     A         ' AREA RANGE   LMA   LMB ITB   PRINT',/)
      WRITE(6,9510) IR,NRM,PMIN,PDA,PDB,LOCMAX,ISP ,L  ,L  ,ITR,IP
      WRITE(6,9653)
      HTL=0.0
      HTM=0.0
      ITMAX=1
      ITAMAX=1
      ITBMAX=1
      NTMAX=0
      IHMAX=0
      NSA=0
      NSB=0
      NLOST=0
C
      NRUN=1
      FISPC=ISPC
      QA=1.0-PDA
      QB=1.0-PDB
      LMP=LOCMAX+1
      LMH=LMP/2
      FLMPR=1.0/FLOAT(LMP)
      LC=LMA-1
      LPV=LM +L
      L  P=L  +1
      L  A=L A
```

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